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Grinding and fine finishing of future automotive powertrain components

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ABSTRACT

The automotive industry is undergoing a major transformation driven by regulations and a fast-paced electrification. A critical analysis of technological trends and associated requirements for major automotive powertrain components is carried out in close collaboration with industry – covering the perspectives of OEMs, suppliers, and machine builders. The main focus is to review the state of the art with regard to grinding, dressing, texturing and fine-finishing technologies. A survey of research papers and patents is accompanied by case studies that provide further insights into the production value chain. Finally, key industrial and research challenges are summarized.

1. Introduction

The automotive industry is the primary driving force behind advances in grinding and fine-finishing machines [250] and processes [85]. The demands for higher efficiency through downsizing and improvements of powertrain components lead to unprecedented performance in terms of reduced fuel consumption and emissions. These gains have been achieved through the latest advancements of the internal-combustion engine (ICE), the electrification of the powertrain, innovative designs for components, improved materials, and recent developments in manufacturing technology, which include grinding and fine-finishing operations.

Freedom of mobility and transport of goods are deeply rooted in the history of humankind. Today, transport is undergoing a great transformation. The demand for change is driven by social factors as well as the manufacturing sector. The automotive industry is facing the most extensive transformation since Otto built an ICE in 1876. The push towards the electrified powertrain gained major momentum after the Volkswagen emissions scandal in 2015. Driven by the demand of more stringent regulations and more environmentally aware consumers, a number of automotive OEMs announced their commitment towards "e-mobility", "zero emissions" and "decarbonization", largely at the expense of diesel engines. Volvo Car Corporation, for example, announced in 2017 that the company will not develop any new diesel engines as the cost of reducing emissions is not deemed sustainable. A rapid transition from ICE-using gasoline and diesel vehicles to hybrid-electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and (battery) electric vehicles (EV) is logical in view of urban mobility and future cities. At the same time, such a transition is perceived by some as "cannibalization" of the automotive industry, without clear life-cycle assessment (LCA) of the emissions produced in electricity generation [210] or the impact of the materials cycle [168]. Regulations are often not based on comprehensive LCA, but rather on simplified indicators such as "wheel-to-tank", which favor EVs [145]. Another aspect might be insufficient leveraging of the CO_2-reducing performance of the latest generation of diesel engines running on synthetic (renewable/bio) fuels [1,4,89,228]. In Japan, a drastic advance has also been made toward fuel-cell electric vehicles (FCEV), e.g. Toyota Mirai [263]. In China [143] and South Korea [117], hydrogen-powered vehicles are gaining momentum, whereas Europe lacks the required infrastructure, with the exception of Germany. In contrast to EVs, which are more suited to lower-weight vehicles and short driving ranges, FCEVs could optimally cover heavy-duty transport and long driving ranges, which are now dominated by the ICE. In Europe, Volvo Group and Daimler announced a joint production of fuel cells for heavy-duty trucks. FCEVs combine the advantages of EVs and ICEs [78]: zero tailpipe emissions, high efficiency, long ranges and short refueling time. The latest ICEs, hybrids (see Section 2.1.), EVs and FCEVs all directly affect the future design and production of powertrain components. This will transform the entire production value chain, from material-conversion processes, machining to grinding and fine finishing, which are in the focus here.

The objectives of this paper are twofold: (i) to provide a comprehensive insight of the future trends in the automotive industry with respect to the finishing of automotive powertrain components, and (ii) to review the developments in grinding and fine-finishing technologies

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over the past decade. The paper is structured as follows. Section 2 begins with a brief description of the different vehicle powertrains and then continues with insights into emerging trends and how regulations affect production in the automotive industry. This is supplemented by interviews with industry professionals and through a dedicated survey. Section 3 discusses the requirements for bearings, gears, shafts and new components. Section 4 addresses the changing production chains. Section 5 discusses the state of the art with respect to grinding, dressing and texturing. Furthermore, the paper aims to provide an update of the 2009 CIRP keynote titled "Industrial challenges in grinding" [185]. This update will likely be the last in-depth analysis of camshaft and crankshaft finishing as future development of these classical engine components is in decline. In contrast, gears have a brighter perspective. Therefore, it is also intended to follow up on the 2008 CIRP keynote titled "Gear finishing by abrasive processes" [114]. Section 6 discusses fine finishing of automotive powertrain components, followed by a short sequel of the 2017 CIRP keynote "Recent advancements in grinding machines" [250] in Section 7. The paper concludes with a summary of the major industrial and research challenges and a brief outlook for the future, in Section 8.

2. Future trends in the automotive industry

2.1. Automotive powertrains

The transition from ICE to electrified powertrain evolved from the hybridization of the vehicle-propulsion system, which aims to improve the vehicle's efficiency (e.g. fuel consumption) and reduce (tailpipe) emissions. Toyota revolutionized the automotive industry in 1997 by launching the Prius, the world's first mass-produced HEV. The HEV powertrain combines an ICE and an electric motor. Here the motor is powered with a battery that is charged mainly by the ICE and regenerative braking.

Newer vehicle-propulsion systems often feature more complex hybrids [115] which, for example, allow a decoupling of the rotational speeds (of the electric motor and the ICE) while still allowing both to provide traction. A benchmark example of such a dedicated hybrid transmission (DHT) is the fourth generation of Toyota's Hybrid Synergy Drive (HSD), including the P610 transaxle (Fig. 1) with a parallel-shaft layout, a reduced number of components, and 20% lower mechanical losses [230].

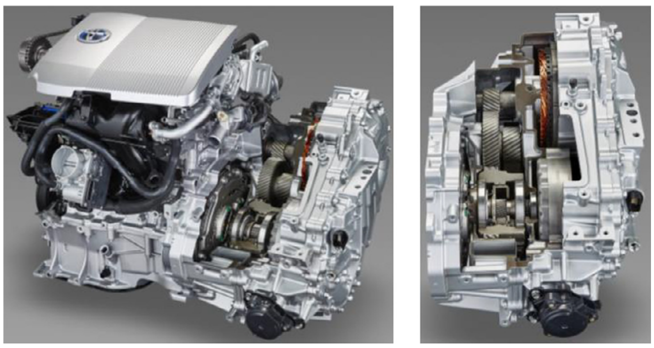

Fig. 1. Toyota P610 transaxle (Toyota Motor Sales, USA, Inc.).

The DHT exemplified here is comprised of:

- Power-split device: a single planetary-gear carrier, an external counter-drive gear (including an internal/ring gear to engage the planet gears), and a sun gear;
- Drive-gear shaft connected to one of the two AC motors;
- Counter-driven stepped gear with two sets of external teeth on the same shaft (for receiving torque from both the drive-gear shaft and the counter-drive gear); and,
- Output drive-gear assembly including a differential.

A further reduction of components is possible with series-parallel DHT, such as featured in the Honda i-MMD powertrain system containing two motor generators and an engine-drive clutch (without the transmission). In a serial mode, the ICE powers a smaller generator to produce electric power, whereas the larger traction motor is connected to the drivetrain. At higher speeds, the clutch is closed, and the ICE is connected directly to the drivetrain. The optimal switching here requires intricate control. The special feature of this DHT is hence a clutch for disengaging the ICE from the wheels [37] and for connecting the two motor-generator units. Further advancement of the DHTs will require the balancing of mechanical and electrical complexity for the different vehicles.

Tesla popularized a battery-electric powertrain, where the number of traction motors (taking the role of an engine) has been steadily increasing. The power produced by the electric motors is transferred to the drive axes via a gearbox. Tesla's gearbox is a two-step reduction transmission using a total of four helical gears (i.e. a small output gear for the rotor shaft, a large input gear for the intermediate shaft, a small output gear for the intermediate shaft, and a large input ring gear for the differential). It has no possibility for a varied transmission ratio (shifting gears) and is thus considerably less complex than the DHTs. Its purpose is to reduce the output speed from the motor in two steps (i.e. single-speed transmission) and multiply the torque. Next to gears and bearings, this gearbox further includes an (open) differential. Further EV evolution comes from newcomers such as Rimac Automobili, which produces a fully distributed powertrain (i.e., where each wheel has its own electric motor), enabling active torque vectoring. Other innovative EVs are enhancing this concept via in-wheel motor (IWM) powertrains, providing a less constrained design space and using significantly fewer components [16]. Consequentially, this translates into cost-reduction potential [99] − in addition to higher energy efficiency − as the wheels are propelled directly. To illustrate: ICE-driven vehicles have about 167 components, while EVs have around 35 moving/wearing components [97]. Considering this 80% reduction in the number of components, the EV powertrains can notably impact existing production chains.

2.2. Regulation-driven needs

The electrification of the automotive powertrain is to a large extent driven by regulations. For example, the environmental aspects of the automotive industry are legislated via emission-reduction targets for CO_2, NO_2 and particulate matter [222]. Moreover, a number of cities are implementing local regulations to reduce the use of diesel in urban environments, especially for trucks and buses. Examples of these effects are illustrated below, for EU regulations affecting heavy-duty vehicles.

EU Regulation 2019/1242 for heavy-duty vehicles stipulates a target reduction of 30% in CO_2 emission until 2030. This regulation includes incentives for "zero-emission" vehicles (EV) and "low-emission" vehicles (HEV). As diesel engines continue to dominate the heavy-duty segment, it is important to mention the Euro VI regulation, mandatory since 2013, which sets strict emission limits, in particular for nitrogen oxide (NO_x). This regulation drove the development of Euro-VI-compliant diesel engines. EU Regulation EU 540/2014 requires OEMs to ensure noise-reducing measures for engines and transmissions (including automatic, CVT, DHT, etc.) to comply with the allowable vehicular sound level. Then, EU Directive 2011/65 on the restriction of using certain hazardous substances in electrical and electronic equipment also affect lead-containing powertrain components, such as shafts, engine valves and clutches. Finally, EU Directive 2018/2001 on the increased use of energy from renewable sources constitutes important measures needed to reduce greenhouse gas emissions. These regulations require a multitude of solutions, including gas-powered trucks and buses using compressed natural gas (CNG) [196,200] or liquefied natural gas (LNG) [179], after-treatment technologies (e.g. selective catalytic reduction), exhaust-gas recirculation (EGR), and other advanced combustion technologies [50,199]. While EGR is an established solution for reducing NO_x emissions, it increases wear of engine components. An example is corrosion of cylinder liners, which is especially pronounced in fuels such as fossil-free ethanol. The corrosion issue can be solved by

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coating the cylinder liners via plasma spraying of powder materials (metallic, ceramic, metal-matrix composite [139] or some combination thereof [68]). This solution, however, requires subsequent honing of the coating with diamond stones to achieve strict surface-finish requirements [85]. Other requirements for components and their finishing are provided in Section 3.

2.3. Industry trends

A study of industry trends was undertaken to explore the challenges and opportunities in grinding and fine-finishing technologies. The study relied on: (i) executive and technical interviews with industry experts, and (ii) an industry-wide survey. It is important to note that both the interviews and the surveys were conducted during the end of 2020, just prior to the coronavirus (COVID-19) pandemic, which further disturbed the industry with immediate declines in production and the adding of yet another level of uncertainty to OEMs' strategic priorities and decisions with respect to electrifying the powertrain.

2.3.1. Interviews

The objective of the interviews was to explore the strategic high-level trends in the automotive industry and to provide initial input for developing a technical survey (Section 2.3.2). The in-depth interviews covered issues such as disruptive changes, new electrified powertrain components already in production, new demands for existing technologies, challenges vs. opportunities, and perceived threats. Interviewees were carefully selected to include all relevant stakeholders − i.e., automotive OEMs (both passenger and commercial vehicles), suppliers, machine-tool builders, innovative small and medium-sized enterprises (SMEs) and management consultants. Some 20 industry experts were invited and 10 agreed to participate, giving a 50% response rate. The interviewees were segmented as follows: four senior managers (including CEOs), four manufacturing-engineering managers, one head of mechanical design for new components, and one senior management consultant.

The overarching findings are that the biggest drivers of transformation (preventing the industry from doing business as usual) are regulations in different regions/countries. Uncertainty is also rampant, for example with the European Union's expected emissions standard (Euro 7) for petrol and diesel cars, trucks and buses. This type of uncertainty is resulting in very broad scenarios and predictions for future segmentation (and market shares) of the EVs. For example, by analyzing available data from the International Energy Agency regarding the production of EVs, it is possible to infer that nearly 6 million EVs were deployed in 2018, whereas the estimates are that nearly 44 million EVs could be deployed yearly by 2030 [31]. In this scenario, EVs would account for 30% of all global vehicle sales in 2030. However, Bloomberg gives a different outlook, estimating 26 million sales in 2030 [39]. These types of predictions are even broader for commercial vehicles. The adoption of electric buses and lightweight trucks is ongoing and driven by demands for sustainable transport solutions in city environments [181]. For example, Scania recently launched a lightweight (max. 29 tons), battery electric truck providing 230 kW power and 1300 Nm torque. At the end of 2030, the share of electric lightweight trucks could reach 10%. However, such a share for heavy-duty trucks will likely not be reached in decades to come due to the current limitations in battery technology. There is no public prediction available for the FCEV share in this segment as no OEM has yet rolled-out these vehicles into production, beyond running pilot projects with respect to buses.

However, in all mentioned scenarios, the ICE will continue to dominate transport despite a continuous decline in sales. It is very likely that in 20 years still more kilometers will be driven by ICE cars than EVs. In between these two segments, HEVs will have a tangible share. They are currently in focus, especially in Europe, as these vehicles are able to meet the 2030 CO_2 targets. In fact, hybridization goes beyond the engine, as electric motors are not only complementing the ICE, but are also integrating into electrified gear boxes (i.e. transaxles) and axle drives. For example, Scania's early hybridization [12,18] of automated manual transmission towards an electro-mechanical transmission resulted in a 25% reduction in the number of components. Simultaneously, the demand for lightweight components is met via miniaturization and redesign (e.g. wider gears) and improved materials with reduced inclusion content (e.g. clean steels).

In summary, the uncertainty regarding future regulations, market conditions and public opinion is preventing the automotive OEMs from adopting a uniform manufacturing strategy, which can delay critical decisions regarding future investments in production capacity (e.g. new engine platforms). This of course has strong implications on the machine-tool sector, as 30-40% of all machines sold are to the automotive industry. At the moment the biggest opportunities are to be found in the HEV segment. The production of conventional powertrain components is not yet phasing out. However, the state-of-the-art with respect to camshafts and crankshafts is likely reached, with a limited number of further innovations. In comparison, gears have a better outlook as they are still featured in the electrified transmission, although with lower volumes (e.g. reduction and differential gears). Nevertheless, the demand for higher precision in automotive powertrain components is continuing to increase with respect to geometries, tolerances and surfaces. This demand needs to be satisfied via improved grinding and fine-finishing operations at the end of the production value chain.

2.3.2. Industry-wide survey

The objective of this survey was to explore various stakeholders' perceptions in relation to the grinding and fine finishing of future automotive powertrain components. It covered perspectives from OEMs (automotive and machine builders), suppliers, and highly innovative industry entrants. The open-ended survey consisted of 25 respondents (at a 70% response rate) who each provided qualitative text answers. This approach proved effective for the exploratory, interview-type questions concerned. The seven "questions" below summarize the main findings that emerged from the analysis of survey responses.

Question 1: <u>What are the major future trends in grinding and fine finishing of automotive powertrain components?</u>

The majority identified electrification (incl. hybridization) of the powertrain as the dominant future trend affecting grinding and fine finishing in terms of more stringent requirements for: (i) noise (in gears); (ii) geometry; and (iii) surface integrity, including surface roughness (on bearing surfaces). The following quotes further highlight these trends:

- "*Grinding is no longer a traditional finishing method as it is already replacing rough machining in specific applications.*"
- "*Hybrid powertrain will dominate the market during the next decade or two, which will continue to increase the need for grinding and fine finishing.*" And "*For the next 15-20 years, added value by finishing per vehicle will not decrease, as the vehicle production will grow in total.*"
- "*Electrified powertrain will have a major impact as the number/volume of components requiring grinding and fine finishing will be reduced.*"

Question 2: <u>What are the critical considerations as the automotive industry is increasing its focus on electrification?</u>

Several barriers are seen with respect to manufacturing: the OEMs' shifting strategy towards an electrified powertrain, market segmentation, uncertain growth, and an uncertainty in future capacity-building. From the perspective of grinding and fine finishing, the critical consideration mainly refers to lower future volumes of components and more stringent requirements.

Question 3: <u>What are the main component requirements for (i) bearings, (ii) shafts, and (iii) gears in terms of form, accuracy and surface integrity requirements?</u>

The common requirements for all types of components include surface form and texture. The requirements for surface texture include surface roughness and waviness, which to a large extent are determined by the grinding and fine-finishing operations. These requirements mainly include the arithmetical mean height (e.g. R_a) and the total profile height (e.g. W_t). The survey also pointed out an increased use of nonconventional surface-texture parameters in the industry such as the reduced peak height of the roughness profile (R_{pk}) and the material ratio (R_{mr}). Similar observations were found in a dedicated industrial survey on using ISO surface texture parameters [231]. Roundness is the major tolerance of form for bearings and shafts. Furthermore, the requirements for bearings and shafts also extend to surface integrity, with specific thresholds regarding residual stresses and thermal damage. For gears, the major requirements refer to acceptable noise, which is especially important in an EV powertrain. Noise-level requirements translate to reducing surface (geometrical) form errors (e.g. gear flank profile, root relief, pitch) and optimizing the surface roughness and waviness of the flanks. Such requirements drive the improvements in grinding operations, e.g. Liebherr's (i) deviation-free-topological grinding, and (ii) generated-end-relief grinding [161].

Question 4: Which new powertrain components emerged in the automotive industry during the last decade?

- Lightweight balancer shaft with integrated ball- and/or needle-roller bearings;
- Shafts (and gears) for continuously variable transmission;
- Hollow shaft for double-clutch transmission;
- Stepped-pinion gears used in planetary transmissions;
- Electrified transmissions and axles (e.g. counter-drive gear, electric portal axle for commercial vehicles), etc.

Question 5: Have you noticed, or do you expect any changes with respect to materials of automotive powertrain components?

The major trends with respect to materials in automotive powertrain components refer to a wider adoption of clean steels with a (more) controlled distribution and size of non-metallic inclusions. Clean steels with improved grindability are especially attractive for bearing and gear applications. Powder metals are finding applications in gears, being produced by pressing and sintering or by additive manufacturing (powder-bed fusion). The camshafts of ICEs, which were traditionally made of grey cast-iron, are to a large extent now being made of steel. Furthermore, attempts have been made in introducing high-strength bainitic steel to crankshafts and diesel injectors.

Question 6: How are other manufacturing processes affecting grinding and fine-finishing operations?

The survey indicates that hard machining (including gear skiving) is the most complementary machining operation to grinding [122]. This is especially evident in lower-volume manufacturing. Nevertheless, grinding is foreseen to increase due to the cost advantages associated with large-scale industrial grinding. This is further evident with advantages in near-net-shape material-conversion processes (e.g. precision forging), which reduce the need for machining. The following quote further illustrates the need for other manufacturing/machining processes:

- "*Fine finishing of internal gears is still not feasible in production despite significant volume of these components in hybrid transmissions, as well as in EVs.*"

Question 7: Is there a need to develop new technologies for grinding and fine finishing of automotive powertrain components?

The primary development-drivers are more stringent quality specifications and demands for higher productivity. The powertrain production already includes integrated technologies, e.g. for hard-turning and grinding. This integration is application-specific (e.g. gearwheels), where production economics require the majority of the material to be removed by grinding. Other combinations include laser metal deposition followed by grinding, offering possibilities of multi-materials finishing. In this case, there is a need to increase the productivity of additive manufacturing. In addition, there are many niche applications that have limited technological alternatives available on the market, e.g. face grinding of taper rollers.

3. Requirements for automotive powertrain components

The number of components in a vehicle which generates and transmits power is large. These components are primarily associated with the ICE/e-drive and transmission. To narrow the scope of this work, a focus is given to critical components that require grinding/fine-finishing and that are largely produced by the automotive OEMs themselves. With this in mind, this paper does not discuss ICE injection/common-rail components, batteries, cylinder liners, pistons, clutches, sprockets, CVT components, driveplates, etc. The requirements for low friction have implications for the use of bearings in all powertrain systems. Therefore, bearings are included in this work.

Each automotive powertrain component is required to deliver a specific performance based on its designed functionality. The interplay between (i) the properties of surfaces and (ii) the finishing processes used to impart surface characteristics to obtain a desired functional performance is reviewed in [30]. In the manufacturing of the components, there are three critical fields for affecting the performance – aside from the product design and the material selection. These are the geometrical accuracy, the surface texture and the surface integrity. The required performance can be achieved by managing the dominant factors listed in Fig. 2.

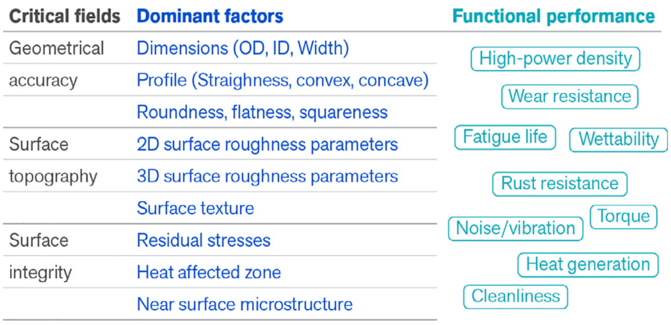

Fig. 2. Functional performance and associated KPIs.

The surface texture of a component depends on the finishing method. A ground surface consists of directional scratches, whereas a hard-turned surface exhibits regular cutting-feed marks. A superfinished surface, in contrast, features characteristic cross-hatch grooves, whereas an isotropic finished surface [82] exhibits no directional marks. These surfaces yield different coefficients of friction when in sliding contact [81]. In terms of residual stresses, superfinishing generates the highest compressive residual stress, followed by grinding. Hard turning, in contrast, produces a residual-stress profile in which maximum compressive stress is not reached at the surface, but rather underneath the surface at a specific depth [81]; it also produces very different microstructures [94,95]. Additional aspects of the effects of finishing processes on surface texture for sliding components is given in [69].

3.1. Requirements for bearings

Bearings in the automotive powertrain are required to achieve a long fatigue life, low torque, high wear resistance, and low noise under conditions of high-stress at contact. The key factors for long bearing life are low surface roughness, profiling of the contact areas to release stress concentrations, and specific residual-stress profiles of the finished (functional) surfaces. The low-torque performance can be achieved by surface-texture control with a reduced surface roughness. The demands for low noise and quiet bearings require improving the roundness, particularly the high undulations per revolution (UPR) waviness of the bearing's rolling elements.

Fig. 3 shows a comparison of torque and heat generation between superfinished (SF) and isotropic-finished (IF) bearings. Compared to the SF bearings, the IF bearings give a surface without any run-in period. Also, it has 25% lower torque and 30% lower heat generation. This is because IF provides a flat-top surface and a higher negative skewness in the roughness profile distribution.

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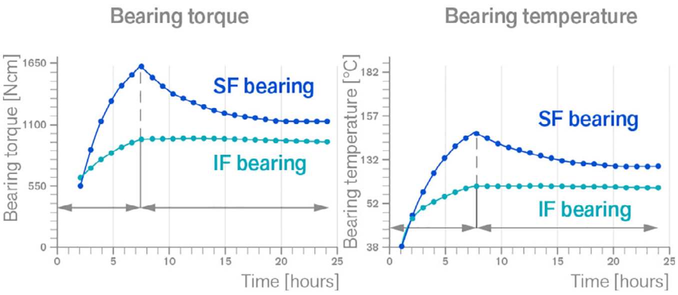


Fig. 3. Comparison of torque and heat performance between superfinished (SF) and isotropic-finished (IF) bearings [81].

Bearing noise can be quantified by the magnitude of vibration or emitted sound pressure, both of which depend on grinding and fine finishing. Fig. 4 shows a comparison between the vibration and sound pressure in (i) a ground and superfinished (GD+SF) bearing, and (ii) a ground and isotropic-finished (GD+IF) bearing. The former combination (GD+SF) produces a significantly lower vibration magnitude and sound pressure because superfinishing has the ability to improve the roundness of the rolling elements, which is not the case for isotropic-finishing. This indicates that superfinishing is key for the achievement of low noise in bearings.

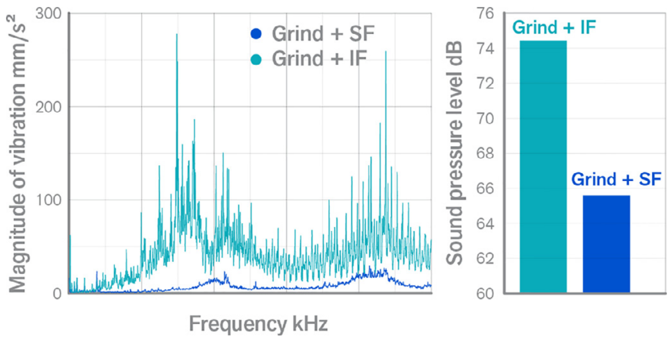


Fig. 4. Comparison of sound performance between pre-ground superfinished (SF) and isotropic-finished (IF) bearings [81].

3.2. Requirements for gears

The efficiency of gearboxes used in commercial vehicles is usually high, typically around 90-97% [92]. The energy losses in gear boxes originate from different sources – such as the gears, bearings, and auxiliary units [164]. In addition, the load-carrying capacity can be improved by reducing friction, which can be achieved by gear-surface modifications and coatings [19,20].

The specific requirements for gears in the commercial-vehicle segment primarily involve load-carrying capacity and fuel consumption, whereas requirements for passenger cars mainly involve optimization of noise, vibration and harshness (NVH). These requirements have an impact on the production of all transmission components with respect to geometry and surface texture. Geometrical requirements typically include the topology of the tooth flanks. A twist (or bias) on the gear flanks inherently develops due to specific process kinematics [23] in both continuous generating grinding and discontinuous profile grinding. The tolerancing of tooth-flank modifications, taking into account process-related twist, is covered in [88], whereas tooth-modification design and simulation is covered in [123]. Avoiding a twisted tooth flank or achieving a certain designed bias deviation is a major challenge in the grinding of gears [63] as it requires careful dressing and axial shifting (of the center distance) between the grinding worm and the workpiece [73]. In view of surface roughness, a standard gear-grinding process can achieve R_z on the scale of 2.5-3 µm. Finer surfaces, e.g. R_a=0.05µm or R_z=0.5-1µm, require grind-finishing of gears utilizing segmented grinding worms that contain a portion of the wheel with fine abrasives in a resinoid bond [244]. This offers surface-quality-related benefits, for example achieving a 75% reduction in the R_{pk} (e.g. from 0.33 to 0.08 µm) and >90% R_{mr}.

Geared components in automotive powertrains also face requirements regarding weight and functional integration. Functional gears manufactured by forming have better performance due to an unbroken grain-flow pattern and strain hardening. Conventionally, bulk-forming operations – such as die forging, extrusion or orbital forming [79] – are applied in single- or multi-stage processes as well as incrementally [75]. In terms of lightweight potential, the forming of sheet material is a promising approach. However, careful control of stresses and strains requires sheet-bulk metal forming [162] and plate forging [175]. In this context, upsetting and extrusion processes are combined with a conventional deep drawing process to manufacture functional components with an external gearing [208]. Due to the high material volumes required to form the functional elements, measures to extend the process limits are necessary. Some approaches for this are the use of semi-finished products with a defined material pre-distribution [242] or the application of tailored surfaces [163] in order to control the material flow. Furthermore, hybrid approaches are used to realize increased lightweight potential [252]. These developments will likely disrupt traditional production chains, as discussed in Section 4. The advances in the forming of gears will certainly reduce the machining allowances. However, the requirements for a precise final geometry and functional surfaces on the gear flanks will sustain the necessity of using gear grinding and fine finishing.

3.3. Requirements for shafts

After more than a century of camshaft and crankshaft use in ICEs, these classical engine components have likely reached maturity in terms of design, materials and manufacturing. The driving forces behind these advancements are OEMs and Tier-1 suppliers, whose filing of patents seems not to have halted in the last decade. Although there are no camshafts in electric vehicles, these components are still critical for the latest generation of ICEs and HEVs, especially in the heavy-duty segment. The demands are still high, which pose real challenges to grinding and fine-finishing operations such as superfinishing.

3.3.1. Camshafts

The fundamental design and operating principle of a camshaft have not changed since the early ICEs. The 2009 CIRP keynote paper titled “Industrial challenges in grinding” [185] addressed the benefits of using lightweight assembled camshafts consisting of forged cam lobes made of bearing steel (R_a=10-12μm) or powder-based metals which are shrink-fitted onto hollow steel tubes. In some cases, a gear wheel can be similarly fit onto a camshaft tube [58]. Assembled camshafts are common nowadays in both passenger-car and heavy-duty ICEs. They can contribute to significant weight reduction (e.g. 45%) compared to conventional (cast and/or forged) camshafts [205]. The modularity of an assembled camshaft offers more flexibility with respect to component design, for example in the case of a concentric camshaft for a variable valvetrain [257] where one set of cam lobes is assembled to an outer tube and the second set of lobes is attached to an inner drive shaft.

The characteristic element of a camshaft is the cam lobe, with its distinctive non-round geometry. To ensure optimal camshaft operation, the parallelism and circular run-out between the cam lobe and a bearing surface of a camshaft must be on the scale of 0.2 μm. As each cam lobe is continuously in contact with a bucket tappet or roller, the surface of a cam lobe is subject to load, causing wear. To increase their wear resistance, cam lobes are heat-treated – e.g. via induction hardening, in the case of heavy-duty diesel engines, to obtain a hard layer of 60-64 HRC with a depth of 2-5 mm. Another major requirement is the reduction of friction in the valve train, which contributes approximately 15% of total engine friction. Friction-induced wear of the lobes also affects the movement of the follower and, hence, the operation of the engine [176]. Approaches to friction reduction include (i) coating [15] and (ii) finishing technologies [226]. The sliding friction between a cam lobe and a contact partner can be reduced by coatings. Research by Nissan Motor Company showed the potential of using coatings to reduce friction in the cam lobe interface featuring a bucket tappet [262]. The obtained friction reduction depends primarily on the coating itself. The friction reduction in case of diamond-like-carbon (DLC) coating was nearly 45% compared to a reference steel valve. Chemical-vapor-deposition coatings demonstrated a friction reduction in the range of 20-25% compared to a reference steel [262]. DLC coatings were also tribologically investigated in bucket tappet/camshaft contacts under realistic operating conditions [53]. The research at Ford Motor Company extended the investigation to wear evolution on a bucket tappet/cam lobe with respect to both coating and finishing [66]. The results suggest that friction reduction can be achieved primarily by improving surface finish, and secondarily by applying coatings. Second to coating of bucket tappets, coating of cam lobes can offer further tribological benefits. This solution can reduce friction torque by 30% and is offered by suppliers that coat ground cam lobes prior to assembly. Another viable technology to deposit wear-, corrosion- and temperature-resistant coatings is thermal spraying [227]. Finishing of coatings is challenging [96], but is often not needed. For example, DLC coating increases the surface roughness at insignificant amount and does not mask the characteristic cross-hatched surface marks [198].

The camshaft production chain can include hard turning with cBN inserts for roughing, facing and finishing of cam lobes. Sandvik Coromant demonstrated that 1,000 cam lobes could be machined with a single cutting edge. Nevertheless, finishing of cam lobes still most often includes grinding, as well as superfinishing using abrasive stones and/or tape [85]. The grinding allowance can be substantial, e.g. 0.4-1.2 mm, which necessitates the use of cBN grinding wheels. Grinding and abrasive fine finishing offer unique performance with respect to the achievable R_a and R_z, in addition to requirements for (i) level difference on the core surface (R_k), and (ii) reduced peak and valley depth (R_{pk} and R_{vk}). Surface texture requirements can further include W_t. For a more detailed overview of surface-texture parameters, refer to [45]. The conventional roughness-profile parameters can be replaced by using newer, more meaningful areal parameters which are, however, not widely used in the industry [231].

Another example of the advanced camshaft-driven valve train is electromechanical (or hydraulic) cam shifting [222], which is available for both gasoline and diesel ICE. The camshaft adjuster/phaser features a stator and a rotor connected to the camshaft, as well as a high-transmission-ratio gearbox [222]. In addition, in an ICE/hybrid, the "free-valve ICE" concept without a camshaft features fully variable valve actuation, which is based on a programmable electro-pneumatic valve combined with a valve spring retainer [90]. This concept has demonstrated excellent performance and is featured in Koenigsegg's Gemera vehicle.

3.3.2. Crankshafts

The crankshaft is arguably the most critical component of an ICE as it transfers power through the drivetrain system of a vehicle. The design of a crankshaft is very complex and has been subjected to continuous adaptation and improvement over decades. A crankshaft is made by forging or casting and consists of bearing journals and crankpins. Fig. 5 shows a crankshaft of a heavy-duty diesel ICE and a (zoomed-in) crankpin with a sidewall connected to a bearing surface via a radius. Requirements are set to control the crankshaft's functional performance, such as: (i) piston stroke length, (ii) mechanical strength (e.g. bending and shear) to withstand combustion-induced forces, and (iii) the tribological requirements at the contact surfaces.

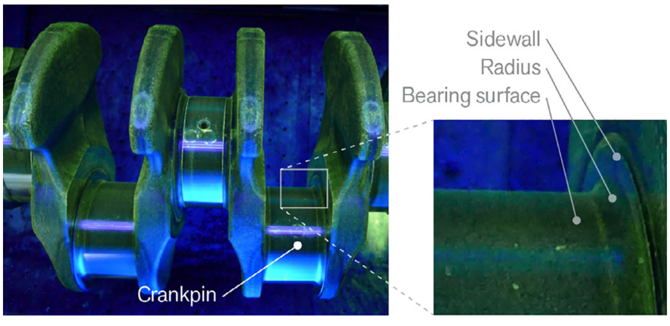


Fig. 5. Crankshaft, with a zoomed-in view of its crankpin [57].

The most critical part of a crankshaft is the sidewall of the crankpin. It is subjected to the highest stresses, which are caused first by alternating bending, and second by resonant vibrations due to centrifugal forces. These highly concentrated stresses can lead to fatigue fracture, which is one of the major causes of crankshaft failure [64]. Crack initiation can be caused by improper hardening [255]. The cracks are often revealed using magnetic particle inspection only after grinding − even if they are caused earlier in the production chain. Moreover, ground crankshafts undergo a rigorous quality assessment, including: (i) in-line measurements of Barkhausen noise (BN) [54], with rejection of above-threshold or extremely low BN values; and (ii) destructive testing including etching and/or XRD-measurements of residual stresses. Compressive residual stresses are required on ground surfaces for improved fatigue life [266]. Other approaches for minimizing failure of crankshafts include improvements of steel grades (with controlled inclusions), designing a larger radius to reduce the notch effect, and cold-rolling of the radius to strain-harden the surface [256]. These observations are important, as the causes of crankshaft failure in the industry are very often wrongly associated with (improper) grinding. Indeed, severe grinding burn − such as rehardening − can lead to cracking of the ground surface. However, the location of the observed cracks is frequently found in the forging "flashline", where the hardness is lower and stresses are concentrated.

Geometric tolerancing and surface-roughness requirements to a large extent determine the grinding and fine-finishing operations. Bearing journals are aligned with the main axis of crankshaft rotation, so the parallelism requirements for the journal bearing surfaces are in the range of 5-10 μm. Crankpin requirements further include perpendicularity, run-out and circularity of the bearing surface (e.g. 5 μm). To meet these requirements, crankshaft grinding is necessary. In terms of surface roughness, a typical R_a requirement is 0.25 μm [266]. Another major requirement is waviness, as this affects the load-carrying capacity [135]. The required waviness amplitude (e.g. 5-10 μm) typically necessitates the use of superfinishing after grinding, utilizing stone and/or tape finishing [85] of the crankshaft bearing surfaces. Note that the surface-finish requirements for the crankpin radius and the sidewall are usually not so tight (e.g. R_a = 0.8-1 μm).

The most recent requirements for crankshafts include: (i) texturing of the bearing surfaces to achieve higher hydrodynamical pressure and reduced friction [134], and (ii) creating a curved (e.g. concave) bearing surface [77]. More details are given in Section 3.5, below. The optimization of the bearing-surface contour aims to maximize the load-bearing area and to improve lubrication during operational displacements, i.e., between the crankpin and the connecting rod. The scale of a typical pin curve is on the order of 5 μm from the nominally flat bearing surface [11]. This new geometry can be generated in the final grinding increments, subject to correct dressing. Modifications of superfinishing with stones and tape (including tape shoes) are also required.

3.4. Requirements for new automotive powertrain components

Recent powertrain architectures, such as P4 hybrid systems and EV applications, integrate power electronics with a transmission (incl. differential) for transferring torque to an axle. Gears are found even in the most advanced EV applications, such as in a powertrain with extreme performance (Fig. 6).

Electric motors can generate a considerable amount of heat. Therefore, it is important to cool the rotor and the stator. As early as 2009, Tesla patented a cooling system for a rotor assembly [269]. This invention included a hollow rotor shaft with an integrated feed tube rotating at the same speed to facilitate propelling coolant through the assembly. Rotor shafts, shown in Fig. 7, form the heart of the electrified powertrain as they are central to the electrical motor and first "collect" the torque between the stator and the rotor. The rotor shaft

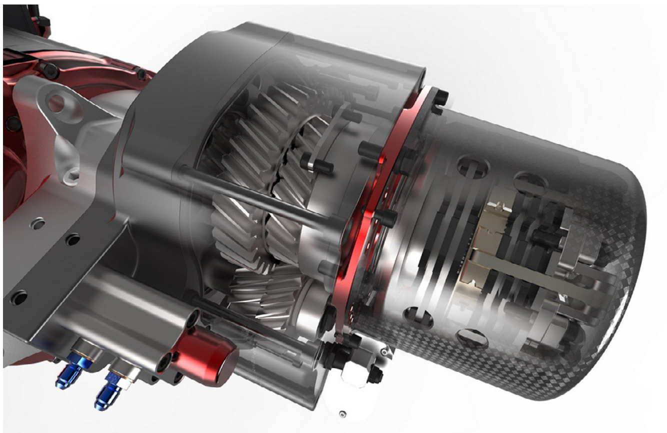


Fig. 6. Rimac Automobili's (Concept_One) high-speed dual permanent-magnet electric motor (600 kW peak power, 12,000 RPM) featuring a double-clutch two-speed gearbox [148].

Fig. 8. Shaft in a typical HEV clutch (Hirschvogel Automotive Group).

then conveys the torque into the transmission. Demands for such electrified-powertrain applications include minimum assembly space and lightweight design. Consequently, automotive rotor shafts feature a higher outside diameter, so the generated torque is higher in a smaller assembly space. Thus, these components are widely designed as hollow shafts with small wall thicknesses (5-10 mm) in order to save weight. Typical materials for this component are medium carbon steel and alloyed steel.

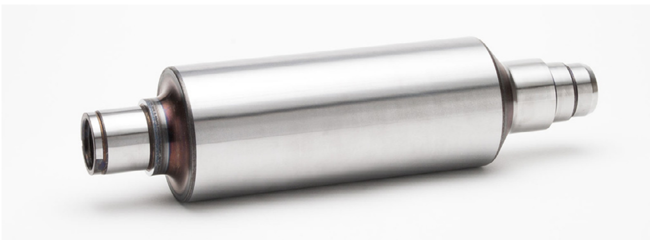


Fig. 7. Rotor shaft with ground functional surfaces (Hirschvogel Automotive Group).

Manufacturing of typical rotor shafts starts from a tube material, followed by a swaging operation, which produces different diameters. The more common production chain includes forging. Here, the bar material is formed (by warm or cold forging) into a hollow, cup-like shaft which is half open. This is done with different extrusion processes. Next, the two different sides of the blank are pre-machined and (laser) welded into a shaft with a closed hollow contour on the inside, followed by turning and rolling to generate the spline. All rotor shafts are then induction hardened in the spline and bearing-surface areas, while some are induction hardened in the area where the electric sheet stack is mounted. Then the bearing surfaces (and mounting surfaces, if hardened) are ground in order to reach the necessary tolerances. The typical requirements for these bearing surfaces are similar to those of conventional shafts, e.g. roundness of 5 μm and surface roughness of R_a = 1-2.5 μm, which can be achieved with grinding and without the need for superfinishing.

In some HEV powertrain transmissions (e.g. VW DQ400E), the ICE and electrical sides of the powertrain are in a state of frequent coupling and decoupling, which requires using a highly loaded and precise clutch. These components also feature bearing surfaces which need to be finished by grinding (Fig. 8).

Additionally, there are a number of components which do not change between the different powertrains. Some of these components are produced using grinding operations, for example constant velocity joint (CVJ) components with bearing surfaces.

3.5. Requirements for textured surfaces

Heavily loaded automotive powertrain components operate under mixed-lubrication conditions. Therefore, the surface characteristics of the components significantly affect the lubrication performance, which determines torque, temperature, wear, etc. Textured surfaces improve the functional performance of automotive powertrain components by optimizing the tribological conditions [61] via maximized hydrodynamic effects, aiming to improve the hydrodynamic lift force and the pressure distribution between the sliding surfaces in a contact. Increasing the lubrication-film thickness for reducing the metal-to-metal contact proved beneficial [86].

Textured surfaces on the cylinder liner and piston have been proven to reduce frictional losses [91], oil consumption and emissions [72]. The most popular technique to texture surfaces involves lasers, while other methods include metal cutting [44], ion-beam processing, etching, and burnishing [72]. Textures significantly affect lubrication – leading to a 5% reduction in fuel consumption [60] and up to a 70% reduction in friction [241]. The geometry of the textured pattern is imperative for friction reduction and oil consumption [239]. An optimal combination of dimple diameter, aspect ratio and density can lead to a reduction up to 70% in the wear rate of the paired components [62].

Textured surfaces are also suitable for bearing surfaces in crankshafts. For example, lightly textured surface produced by burnishing led to a better tolerance of contamination, while a highly textured surface (above 10%) negatively affected the journal-bearing performance [43]. Laser-textured bearings exhibited a friction reduction of 6-18% depending on the texturing density [240]. For texturing of bearing surfaces,

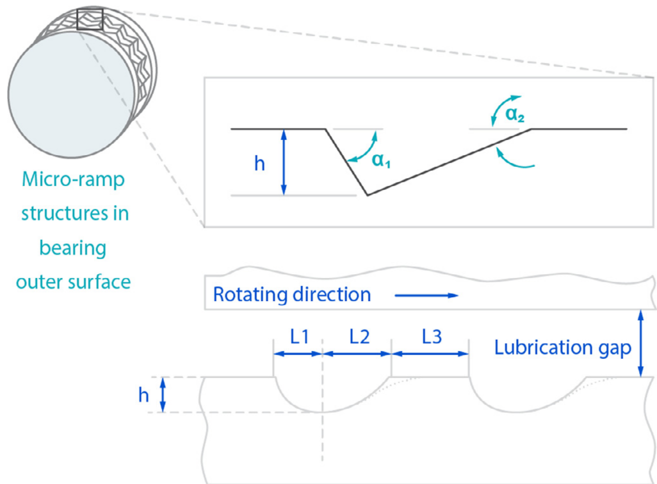


Fig. 9. Bearing surfaces with micro-ramp structures and idealized representation of a textured micro-ramp (based on [202] and [42]).

grinding is a viable alternative to laser as there are no additional investments in terms of integrating laser sources in machines. Crankshaft production always includes grinding, so it is straightforward to use dressing to texture the wheel [183]. The success of grind-texturing depends on the capability of this technique with respect to the dimensional and geometrical requirements of the components. Silva et al. demonstrated texturing of the crankshaft bearing surfaces with pocket-type cavities to control the R_k roughness. Other patterns included chevrons, half-dimples and dimples [3,215]. More recently, micro-ramp structures for crankshaft bearing surfaces (illustrated in Fig. 9) were patented [202]. Here, a concave section of the micro-ramp is determined with lengths *L1* and *L2*, whereas *L3* is the length of the bearing surface. Silva et al. proposed a technique to produce such micro-ramps by grinding [42], where a simplified generic micro-ramp, composed of two sections defined with angles α_1 and α_2, is ground (Fig. 9).

4. Automotive powertrain production chains

Production of varied automotive powertrains necessitates designing production processes to increase flexibility and, at the same time, reduce costs. These production chains are characterized by complexity in which throughput is determined by machine capability and capacity, as well as the grindability of materials and the design of components.

The traditional production chain of automotive components is shown in Fig. 10. Materials enter the chain and are processed through a variety of material-conversion and finishing processes. Material conversion includes metal-forming operations and (soft) machining processes. Thermal treatment is typically performed using a furnace with batch operations, where the cycle time is very long, sometimes several days. The finishing processes consist of grinding, for achieving required geometrical tolerances, and (abrasive) fine finishing, for the control of surface quality and desired texture. Grinding for high-volume production of bearings, for example, uses through-feed-type operations for faces of components. Then, discrete grinding is used for the OD, ID and flange. After that, fine-finishing operations are applied only to the functional surfaces. These fine-finishing processes use part-specific tooling items with a long changeover time.

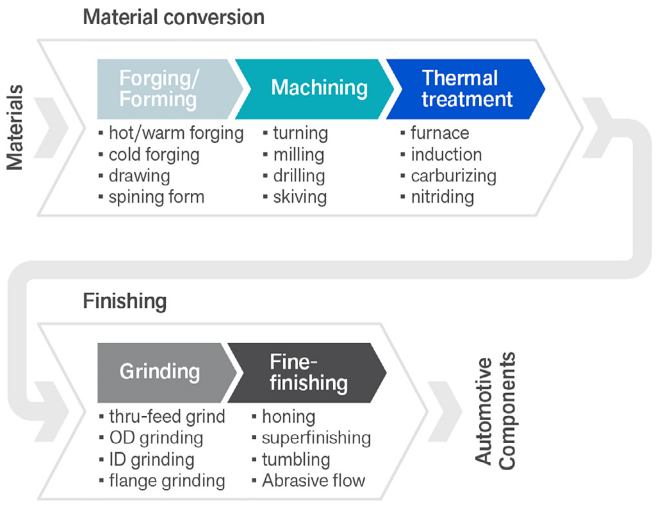


Fig. 10. Traditional production chain for powertrain components.

More flexible manufacturing processes will be required for realizing the production of future automotive powertrain components at reduced batch sizes and shorter changeover [229].

Fig. 11 shows an example of the outlook of the future flexible production chain. Here, the material conversion can be replaced with the near-net-shape conversion using technologies such as near-net-shape precision forming, additive manufacturing (AM) [207] for producing hard-stocks with complex shape, or metal injection molding (MIM). Furthermore, laser thermal treatment can be applied to

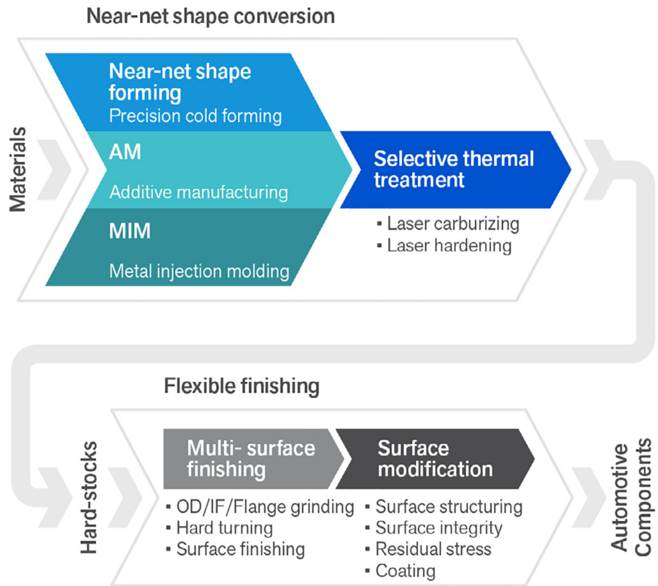


Fig. 11. Outlook of future flexible production chain for small batches.

selected functional surfaces. Such material conversion makes possible to produce near-net hard-stocks without any machining. Multi-surface finishing may include 3D electrochemical machining (ECM) [204] or wire-ECM (WECM) [121]. Moreover, wire-EDM (WEDM) was evaluated in prototyping of gears but was characterized by limited flexibility [22]. The finishing processes can be converted to a more flexible, cell-like, system with multi-surface finishing and new surface modifications. In this scenario, the discrete grinding sequences can be realized with a multi-surface finishing machine, such as an OD/ID/face grinder in conjunction with hard machining and superfinishing. As the through-feed and discrete grinding operations are integrated in a multi-surface finishing machine, the changeover time and tooling costs can be significantly reduced with the increased production flexibility. The surface modification processes, such as surface texturing and coating, can be applied to the finished surfaces to deliver the required surface integrity and functional performance.

Fig. 12 shows a comparison of manufacturing cost profiles for traditional (see Fig. 10) and flexible production chains (see Fig. 11) for precision powertrain components. In the traditional chain, the cost breakdown is about 30% for materials, 30% for material conversion (forming, cutting, and thermal treatment), 30% for grinding/fine-finishing, and 10% for assembly/inspections. In the flexible chain, near-net-shape conversion is estimated to amount to 20% and flexible

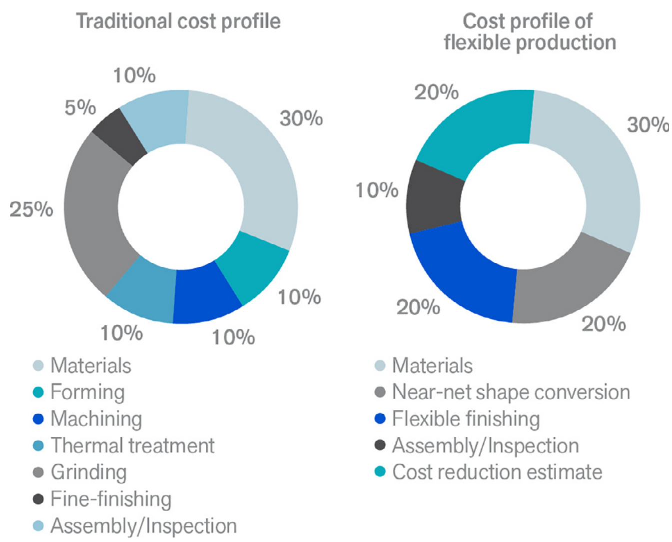


Fig. 12. Cost comparison between traditional and future flexible manufacturing processes (an estimation).

finishing also to 20%. The flexible processes show a potential for 20% cost reduction. These estimations are not component-specific (e.g. size, geometry) and are valid for small batch series. For mass production, the costs associated with the traditional production chain are much lower due to high throughput.

5. Recent advances in grinding, dressing and texturing

5.1. Advances in grinding of bearings

Recent advances in grinding of bearings are illustrated through industrial case studies.

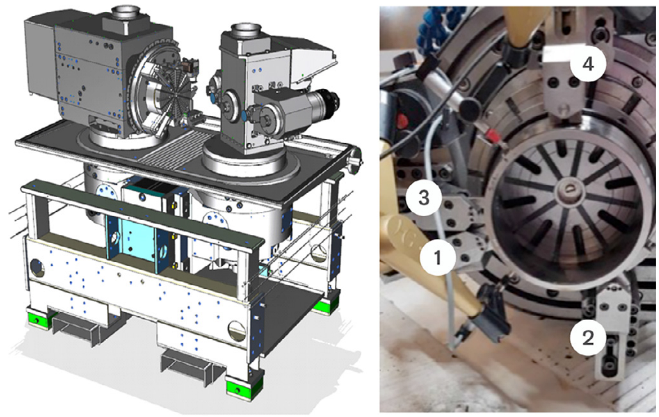
Fig. 13 shows a conventional finishing line for the inner rings of automotive bearings. The line combines through-feed and in-feed grinding methods. The faces of rings are finished by a double-disk through-feed grinder with batch operations as these parts are fed to a discrete in-feed line consisting of OD, ID and flange shoe-centerless grinders, along with an in-feed superfinisher for the bearing raceway. Typical batch sizes are large – e.g. up to 100,000. Productivity is very high, with 10 to 100 pieces/minute for face grinding and 2-5 pieces/minute for shoe-centerless grinding. The changeover times are long: 1-4 hours for the face grinder; 3-6 hours for the OD, flange and ID grinders; and 1-2 hours for the superfinisher. Due to their inflexibility and high tooling costs, these finishing lines are designed for high-volume production, not for low-to-medium-volume production.

Method	Through-feed	In-feed	In-feed
Machine	Double disk grinder	Shoe centerless grinders	Plunge superfinshing
Batch size	1k-100k [pcs]	1,000 – 100,000	1,000 –100,000
Production rate	10-100 [pcs/min]	2-5	2-5
Changeover time	1-4 hours	3-6 hours	1-2 hours

Fig. 13. Common finishing line for automotive inner-ring bearings.

The traditional approach to OD/ID grinding of bearings is to impart each of the features with a separate grinding operation, each using a dedicated machine. An example of a dedicated, high-performance process is internal, traverse cBN grinding [17,93,209]. Such an approach suits high-volume production. However, in the new industrial reality, there is an increasing drive for highly flexible, low-volume batch manufacturing to reduce stock levels. The long changeover times required to set-up traditional production lines currently place limits on the viable batch size and flexibility of low-volume operations. End-users are therefore looking to employ more flexible machines.

An example of a highly flexible grinding machine, consisting of three axes – two rotary and one linear is shown in Fig. 14(a). The axes are driven in the cartesian (X,Z) coordinate system using a linked-mode algorithm embedded within the CNC. Its compact size and elimination of the requirement for stacked linear axes, together with the use of hydrostatic bearing, ensures a compact working zone together with a high stiffness. The shoe-centerless capability is achieved by mounting the support shoes on the work-spindle axis. Three grinding spindles allow the use of multiple wheels to grind ID/OD plane, contoured and spherical features with a single wheel. With shoe-centerless grinding of bearings, a critical aspect of the set-up is the angle of the supporting shoes, which controls the reduction/generation of workpiece lobing. Also, the shoe angles, magnetic holding force and grinding force need to be balanced in order to maintain stable grinding conditions. With higher material-removal rates, it becomes increasingly challenging to use a single set-up to grind both the ID and OD. Therefore, individual set-ups are often used for these OD and ID grinding operations with different shoe positions for each.



(a) Machine configuration (b) Novel shoe setup

Fig. 14. Highly flexible twin-turret grinding machine (TTG Machine, Fives-Cranfield Precision, UK).

A novel approach has been demonstrated on the flexible machine which allows the grinding of both the OD and ID at the higher removal rates in just one machine set-up [219]. The configuration is shown in Fig. 14(b). It employs multiple shoes, the rear (1) and lower (2) shoe for the OD grinding, and the rear (3) and upper (4) shoe for ID grinding. As the OD and ID shoes are separated, they can be optimized for their respective application. When the work-spindle is rotated clockwise, the component is driven into contact with the OD shoes (1&2). When the work-spindle rotation is reversed, the component moves across into contact with the ID shoes (3&4). Compared to traditional machines, this solution has very short changeover times for different bearings, thus enabling highly flexible, single-machine grinding of bearing components.

Another common operation is double-disc face grinding. While this process is widely used in industry, limited research has been published about it [211]. In double-disc grinding, the workpiece rotation can be driven externally, as in a process with planetary kinematics [46,235,236]. In case of a self-rotating process, the sleeve is used to hold the workpiece and the workpiece rotation is caused by grinding forces from the two grinding wheels rotating with a frequency ω_s. Here both workpiece faces are ground with a fixed infeed v_f. The self-rotating process is challenging to control as one of the process parameters defining the grinding mechanics (i.e. workpiece rotational speed ω_w) is also one of the process outputs. Dedicated research is required to obtain a more fundamental insight into the process mechanics.

Modelling of self-rotating double-disc grinding may be based on the distribution of the point-aggressiveness, *Aggr** in the grinding zone, defined as a scalar field that incorporates the process geometry and kinematics at every point in an abrasive contact [55]. Fig. 15

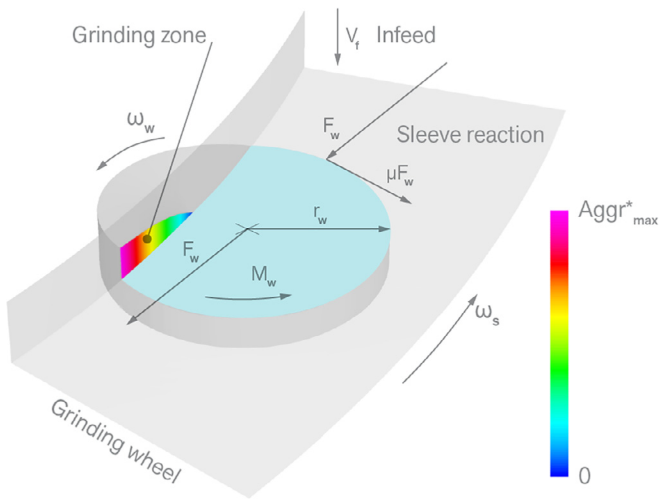


Fig. 15. Illustration of aggressiveness distribution and corresponding mechanics of (self-rotating) double-disc grinding.

illustrates a (cylindrically) symmetric grinding situation, with a workpiece under the grinding wheel. The theory of aggressiveness [55] may be used to predict the resultant grinding force, F_w, and the resultant workpiece moment, M_w. The workpiece rotational speed, which is an unknown parameter depending on the grinding force and the grinding moment, can be calculated by solving the moment-equilibrium equation.

5.2. Advances in grinding of gears

Gear grinding is a key operation in the finishing of hardened cylindrical and bevel gears. In particular, discontinuous profile grinding, continuous generating grinding and bevel-gear grinding have high industrial relevance [113,114]. There are many ongoing research activities driven by the requirements dictated by current and future vehicle transmissions. One of these is efficiency enhancement, achieved via the optimization of the installation space and the reduction of weight, followed by an improved transmission service life with robust performance. Gear grinding can contribute to the achievement of this by:

- Improving surface integrity of the ground tooth flanks;
- Grinding strategies for tailored surface-layer microstructures with increased load-carrying capacity;
- Grinding of asymmetrical tooth profiles / topological grinding of load-carrying optimized gears;
- Optimizing grinding of internal gears (due to increased proportion of planetary gearboxes);
- Reducing of transmission noise by adapted process design when grinding gears for electrified transmission.

A broader and more detailed overview of gear grinding is given in the work of Karpuschewski et al. [114].

The requirement of achieving improved quality at higher productivity requires a better understanding of the surface integrity [140] and technological limits of the gear-grinding processes. For discontinuous profile grinding, Jermolajev et al. introduced surface-layer modification charts, shown in Fig. 16 [103,104]. Considering the grinding process as a source of short-time heat-treatment – i.e. grind-hardening [27] – required measuring the temperature in the grinding zone with a dedicated grinding wheel. The tempering time could be determined based on these temperature measurements, which enabled the quantification of the time-dependent thermal influences. In addition, the critical temperature-tempering time or process limits of the thermal load in the grinding process could be determined [103].

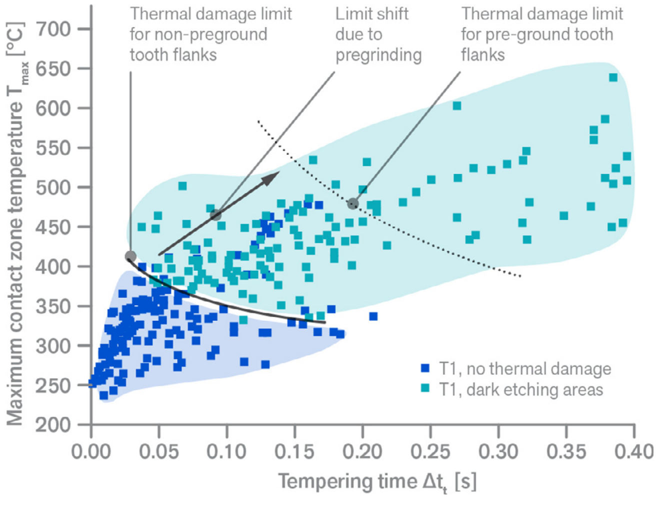


Fig. 16. Surface layer modification chart for profile grinding of the tooth root without pre-grinding (varying material stock removal) [103].

Klocke et al. [124] experimentally determined specific grinding energy in continuous generating grinding. Corresponding modelling and simulation included: (i) simulation of chip geometries and contact conditions (e.g. contact times), and (ii) determination of grinding forces. Another approach involved consideration of the heat flux and the contact time to calculate the heat-flux density in the contact area [49]. This quantity was then used for the prediction of surface integrity of ground gears [197]. Approaches to temperature measurements in continuous generating grinding are given in [120]. By optimizing forces in continuous generating grinding, the aim was to improve the surface roughness of gears and to minimize wear of the grinding worm [24]. Most recently, grinding forces were also modelled for bevel-gear plunge grinding, a typical finishing operation for automotive axle drives [220,221]. Generating gear grinding is also applicable to beveloid gears – i.e., conical involute gears for spatial transmission of power, which is largely used in the latest generation of four-wheel drives [23,26,232].

The capability of continuous generating grinding has also been extended to the grinding of small gears (modules between 0.5-4.5 mm) with interfering contours (Fig. 17). These gears were previously produced with discontinuous profile grinding. Such a process uses small grinding worms (e.g. 55 mm diameter) operating at high rotational speeds up to 23,000 RPM, which is suitable for grinding of drive shafts.

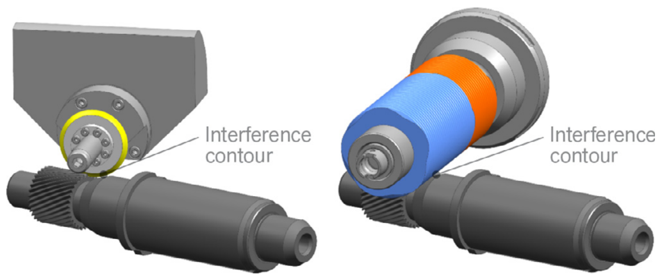


Fig. 17. Finishing of a gear shaft of a hybrid transmission using (i) cBN profile grinding; (ii) generating grinding with combined worm for rough-grinding and grind-finishing (KAPP NILES GmbH & Co. KG).

The thermal-treatment of gears for increased load-carrying capacity is getting more attention. It was shown that carbonitriding leads to a surface-layer microstructure high in retained austenite (≥ 50 vol.%) and hard precipitates [146] that enhance the load-carrying capacity – but at the expense of reduced grindability [98]. This retained austenite causes greater grinding-wheel clogging (loading), and the hard precipitates cause greater grinding-wheel wear, both of which must be compensated for by more frequent dressing intervals. For process monitoring, it was demonstrated that spindle power is an appropriate indicator for optimizing dressing [98]. Moreover, it was shown that optimized grinding-fluid supply is essential in reducing the thermally induced damage to the ground surface layer [191].

As briefly outlined in Section 3.2, automotive transmissions are increasingly equipped with asymmetrical gears whose design is optimized to the (load) application. This leads to special requirements for the grinding and dressing processes. In recent years, discontinuous profile grinding and skive hobbing have been used for the finishing of asymmetrical gears in spite of these processes not ensuring maximum gear quality or minimum cycle time. Finishing of asymmetric gears is also possible with continuous generating grinding owing to a software-based modification of the dressing to obtain an asymmetrical wheel and a modified centering method [161]. With the changed centering, the grinding conditions on both flanks become more equal. Consequently, the risk of grinding burn or loss of gear quality due to grinding-worm wear can be significantly reduced [161].

As an extension of topological grinding, a new process variant, described in [147], leads to a continuous point contact between the tooth flank and the grinding wheel due to adapted kinematics in profile grinding. With topological generating grinding, all conceivable modifications on the tooth flank can be realized. Primarily, this process can be used in prototype production, for example to assess the effects of different modifications on load-carrying capacity and NVH in gears [147].

Since the demand for planetary gearboxes for HEV and EV is constantly growing, the number of internal gears required is also increasing. Therefore, the need for highly productive processes for grinding and fine finishing of internal gears is also rising. For example, continuous generating grinding of internal gears with barrel-shaped wheels at large crossed-axes angles (20-35°) is presented in [259]. Initial investigations have shown that gear quality levels between IT3 and IT5 can be achieved with a cycle time suitable for automotive mass production. Fig. 18 shows the grinding worm and the process principle for this application.

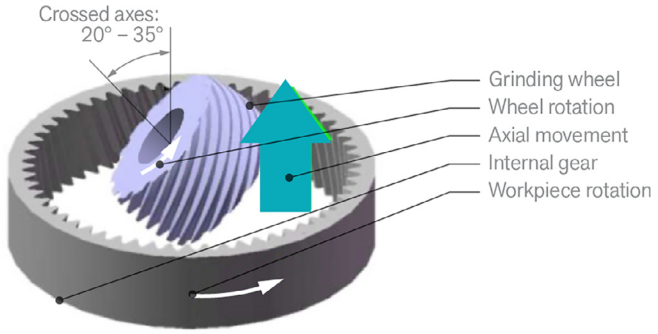


Fig. 18. Continuous generating grinding of internal gears with barrel-shaped grinding wheels (Mitsubishi Heavy Industries, Ltd., Japan).

In addition to reduced roughness [249], high potential is seen for surface structuring of the tooth flanks for improved noise emission in the gearbox. An extensive study on noise generation in powertrain transmissions based on process-specific tooth-flank topographies was carried out by Jolivet et al. [107-109]. For this purpose, gears were finished by continuous generating grinding and honing. Significant differences in noise generation, e.g. frequency domains of the vibration sources, were found for different tooth-flank topographies [107]. Since these experiments were carried out dry, further investigations under flood conditions using grinding oil were carried out to investigate the influence of the fluid on noise generation. It was found that although there is an influence of the fluid, the process-specific tooth-flank topography is the dominant factor regarding noise generation [108,109]. Noise-oriented tooth-flank surface structures are increasingly being optimized using numerical methods [25,51,188], whereby the generation of these structures by grinding poses a challenge. The first approaches in continuous generating grinding included an adapted-shift strategy, the so-called "structure shifting" or "low-noise shifting". More discussion on the fine finishing of tooth flanks is given in Section 7.2, covering gear-honing machines.

5.3. Advances in grinding of shafts

Grinding of automotive/engine shafts to a large extent involves customized OD-grinding operations for camshafts and crankshafts, as discussed below. Centerless grinding is also traditionally used for grinding of shafts, ranging from gear shafts to turbo shafts. Centerless grinding can be classified as: (i) a through-feed operation [56], which is common in bearing applications; or (ii) a plunge operation [10,130], used for example in grinding of gear shafts or camshaft journals. A detailed review of centerless grinding technology is given in [83].

Centerless grinding configurations can also be more complex, for example when simultaneously grinding multiple surfaces. Fig. 19 shows the cut section of an ICE turbocharger. The turbo-shaft has

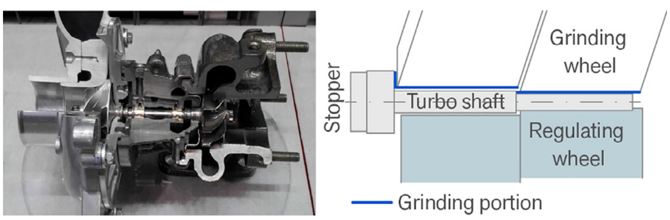


Fig. 19. Multi-surface simultaneous angular-centerless grinding for turbo-shaft production (Tohshin Seiki/Tohshin Technical, Japan).

multiple surfaces (2-3 OD surfaces and flange face) to be finished by centerless grinding in a single setup. The conventional method for finishing is to apply a center-type cylindrical grinding method where each OD is finished by infeed grinding one by one. With this method, it is difficult to achieve the required accuracy with the aimed productivity due to the low stiffness of the turbo-shaft, which has a long length and small diameter. Simultaneous centerless grinding of two different diameters and a flange (shoulder) face is illustrated in Fig. 19. Centerless grinding here solves the issue of the shaft stiffness because the shaft is longitudinally supported by the regulating wheel. In the case of the grinding of a turbo-shaft with 8 mm diameter and 95 mm length, a high-precision, high-stiffness, angular-centerless grinding machine from Tohshin was used. The machine has unique features such as a slide design for grinding with a constant center-height angle, a specific angle setup for the angular grinding, low-profile machine design for rigidity, etc. All surfaces including the flange face were finished in a single plunge operation. The cycle time, including the shaft loading and unloading, was 30 seconds. In continuous grinding tests using 90 shafts, the machine demonstrated the capability of achieving along the shaft length a size variation within +/-0.5 μm, a roundness range of 0.5-1.2 μm, and an R_a roughness range of 0.2-0.3 μm. Productivity was increased by 50% and the capital cost was reduced by 20% compared to the traditional center-type OD-grinding method.

5.3.1. Advances in camshaft grinding

Camshaft grinding uses an OD cylindrical-grinding machine to grind non-round cam lobes. This is a complex grinding process, characterized by transient and non-constant geometry and kinematics [54]. For example, the surge in material-removal rate on a cam-lobe flank can cause grinding-temperature surges and localized grinding burn. Moreover, this surge produces higher normal forces, causing the machine to deflect, resulting in form errors on the ground cam lobes [128]. These surge issues drove the machine builders to develop and implement various cycle-optimization methods such as: (i) grinding with constant speed [116]; (ii) grinding with constant specific material-removal rate, Q'_w [158]; or (iii) grinding with constant power, P [159]. The last two cycle optimization algorithms are commonly provided with machine tools and embedded in their CNC. Unfortunately, they do not fully solve the issue of grinding burn as they do not consider grinding temperature as the input to optimization. Research into non-round cylindrical grinding demonstrated that the incorporation of thermal modelling to run the process at a temperature just below the burn threshold leads to a much shorter grinding cycle compared to other optimization strategies [127]. The thermal modelling employed in this work included Jaeger's moving-heat-source theory [102] with a triangular heat flux [153]. In addition, numerical thermal modelling based on the finite-difference method [213] or computational fluid dynamics [165] can more comprehensively address complex boundary conditions, but these models are not practical for real-time process control and integration with machine control systems. The concept of constant-temperature grinding based on analytical thermal models, initially developed for non-round cylindrical grinding [129], has been adopted to cam-lobe-grinding geometry and kinematics [128]. The constant-temperature process was assessed against the constant-Q'_w, and the constant-P methods in an industrial environment. Fig. 20 shows how the workpiece rotational speed decreases during the surge region and increases during the light-cut cylindrical region, speeding up and slowing down during each workpiece revolution. Here it can also be seen that the currently used, commercially available control algorithms slow the workpiece speed more than necessary, which leads to longer cycle times and a situation when the cam lobe spends more time in the high-temperature zone, increasing the risk of grinding burn. The dotted line in Fig. 20 represents the idealized speed if machine limitations, such as jerk, are not taken into consideration. These limitations, which are included in the constant-temperature model, have a significant effect on process realization and efficiency. These machine-tool aspects are further discussed in Section 7.

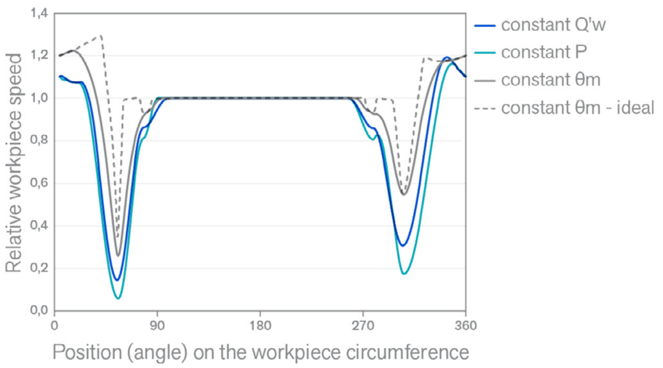


Fig. 20. Output workpiece rotational speed for different process-control strategies, including the constant-temperature process [128].

Grinding often entails a compromise between productivity and quality, with shorter cycle times being achieved at the expense of higher temperatures, rougher surface finishes and poorer dimensional tolerances, even for highly optimized processes. It was demonstrated that high-speed grinding is beneficial for achieving higher quality, but at a slightly reduced productivity [54]. This analysis also provided an analytical "proof" of the grinding sweet spot, i.e., grinding conditions where the specific-energy curve straightens out. Finally, the constant-temperature process underwent a rigorous production part-approval process in industry, followed by patenting [126] and then implementation in Scania's production lines.

5.3.2. *Advances in crankshaft grinding*

Grinding of crankshafts is particularly challenging with respect to surface integrity, as surface roughness and residual stresses significantly influence the operational performance of a crankpin [266]. In contrast to camshaft grinding, limited research is available about the fundamental mechanics of the crankshaft-grinding process. Grinding of crankshafts with vitrified cBN wheels has been the industrial state of the art for the past 15 years.

The challenge when grinding a crankshaft is the changing process conditions across the wheel profile, as shown in Fig. 21. Here, the contact length increases significantly when grinding the sidewall, while the aggressiveness varies across the grinding wheel profile. This can lead to grinding burn on the sidewall [40] and excessive wheel wear within the radius. Current grinding wheels have the same structure across the profile to accommodate vastly different grinding conditions. To optimize the wheel, research has been carried out to investigate the effects of cBN grit shape [151] and grit concentration [149] on grinding performance in crankshaft grinding. The results revealed a correlation between the grit aspect ratio (AR), grinding power and radial wheel wear. More elongated cBN grits (higher AR) exhibit lower power and higher wheel wear. The opposite effect was achieved when using blockier grits. Similarly, changing the cBN concentration also had a pronounced affect [149], particularly, when using more-aggressive grinding conditions. Improvement of surface finish and reduction of grinding wheel wear can be achieved when using a higher concentration of cBN.

Fig. 21. Changes of aggressiveness and contact length across the profile of the grinding wheel in crankshaft grinding.

To address the same challenge, machine builders developed and patented a variety of methods for the determination of feed increments [150]. The two most common grinding methods – implemented on Junker and Fives Landis machines, respectively – include: (i) radial-plunge grinding for roughing [110], where the grinding wheel plunges radially into the crankpin sidewall; and (ii) angle-plunge grinding, where the wheel plunges into the crankpin simultaneously both radially and axially, with increments that can be varied between roughing and finishing [9]. The radial- and axial-grinding methods have been numerically simulated and experimentally evaluated [184]. This study showed that a multi-step, axial face-grinding method was superior, as it minimized the occurrence of the wear-induced "step" in the wheel radius, reducing the need for frequent dressing. This multi-step method, however, is not readily available for direct use in grinding machines. Note that the process planning requires the determination of feed increments for each revolution of the workpiece and selection of an offset to compensate for the run-out of the incoming crankshafts. Non-process solutions to compensate for the run-out include mechatronic measures [172].

Recent research into the fundamental aspects of crankpin grinding was based on analytical modelling and analysis of process geometry, kinematics and temperatures [57]. The kinematics of crankshaft grinding are similar to non-round cylindrical grinding [54] because of the crankpin's eccentricity. In contrast to camshaft grinding, however, the rotational frequency of the workpiece is usually constant. The implementation of a constant-temperature process [127,128] was demonstrated in crankshaft-grinding as well. Here, the thermal modelling requires the experimental determination of the specific energy into the workpiece [54] for the calibration. This characteristic curve captures the effects of the workpiece material, grinding wheel, dressing, cooling, etc. and is specific for every application. Nevertheless, there is sufficient data on specific energy available in the literature [57,154,153] for a wide range of cBN wheels and hardened-steel types, which should ease the work of implementing this technology. The predicted maximum surface temperature along the wheel profile (Fig. 22) shows that the maximum temperature (set at 550°C) is reached at two critical contact points – on the radius and on the sidewall – when plunging the wheel into the workpiece [57]. Refer again here to Fig. 5 showing different portions of a crankpin. In a nutshell, the temperature-controlled crankshaft-grinding algorithm determines the grinding increments so that a predetermined burn threshold is matched in these two critical points [131].

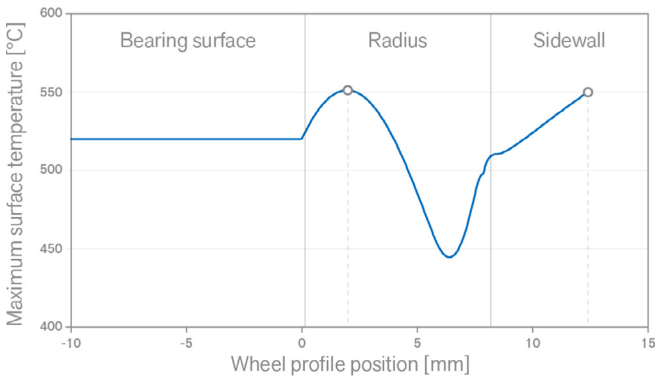


Fig. 22. Maximum surface temperature along the wheel profile [57].

The grinding cycle analysis revealed that the temperature-based method is superior to the reference radial-plunge grinding method in terms of: (i) productivity (min. 25% improvement), (ii) the ability to avoid grinding burn [57], and (iii) in increasing the dressing intervals. The method for the implementation of this constant-temperature process was patented by Scania [131].

5.4. *Advances in dressing tools and grinding wheels*

The outcomes of a grinding operation are critically dependent on the selection of the dressing tool and dressing parameters, which determine the form and topography of the grinding wheels. The various technologies for dressing of grinding wheels were covered in-depth in a 2011 CIRP keynote paper by Wegener et al. [251]. In addition to new bonds, further advancement of the dressing technology requires the investigation of the dressing process from a theoretical and experimental point of view − to understand the relation between the dressing parameters and the final dressing result. In this respect, the fundamental mechanisms governing the dressing process are still not fully understood. This is mainly due to the complexity of the dressing process, which is characterized by a specific geometry and kinematics that involve the dressing tool's interaction with the grinding wheel in terms of numerous collisional events with the abrasive grits in the wheel [55]. Hence, an understanding of the complex dressing mechanisms needs to be achieved prior to optimizing the tool and the process. Recent advances in dressing are discussed here primarily in light of (i) dressing using stationary and rotary tools, and (ii) dressing operations that impart specific macro- and micro-features in the grinding-wheel topography [237]. Note that these advances are not restricted to dressing of grinding wheels exclusively used in the automotive industry.

In dressing with stationary tools, there is no rotational movement of the dresser. Thus, in order to dress the entire wheel surface, the dresser needs to be traversed along its axial direction. Historically, the most commonly used stationary dresser is a single diamond, which can be of different grades (quality). It can be produced in various shapes, e.g. octahedron, dodecahedron. For this type of dresser, extensive literature exists about the diamond-wear mechanisms [142,177,212], e.g. grit flattening, breakage and splintering. Further knowledge includes the influence of dressing geometry and kinematics [8,55,233] on the resulting grinding-wheel topography and, consequently, the imparted surface finish on the ground component [38]. Several types of stationary dressers are available, where the abrasive grits are embedded in a metal matrix or where CVD diamond rods are implanted in a hybrid (vitrified metal) bond system, such as:

- Single-point tool with a geometrically defined diamond;
- Multi-point dressers in the shape of a cylinder, roller or blade (see Fig. 23), with diamonds that are either randomly distributed or set in a patterned arrangement.

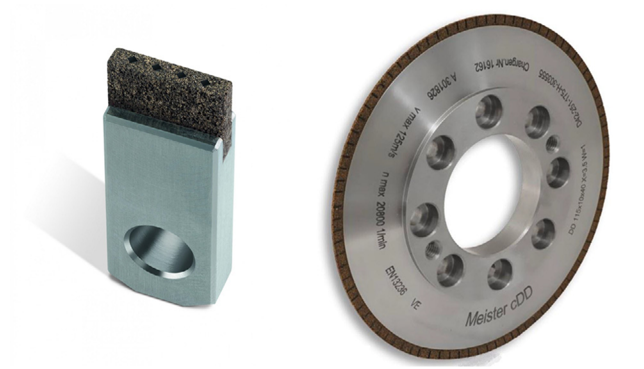


Fig. 23. a) Multi-point stationary dresser; b) rotary dressing roller − both reinforced with CVD diamond rods (Meister Abrasives).

Vitrified and hybrid bonds have several advantages over metal bonds, such as inclusion of pores in the dressing tools. Porous dressers increase the diamond grit protrusion [268] and have the ability to self-sharpen, which leads to less-frequent dressing intervals (i.e. longer dresser life). The applications of porous tools to dress vitrified cBN wheels in the automotive industry include fuel-injector seat grinding, camshaft/crankshaft grinding, centerless grinding, gear grinding, etc.

Rotary dressing tools are used for dressing of both conventional-abrasive and superabrasive grinding wheels, particularly those with complex geometries. A diamond roller typically consists of a specific profile radius containing a single layer or multiple layers of diamonds densely embedded in a non-porous metal bond. Rotary dressers contain diamond abrasives with a specific size and concentration held in a metal bond for sintered form roller or nickel for electroplated roller [217]. Conventional dressers have a random diamond geometry (e.g. size, protrusion, distribution), which makes their optimization difficult. For example, this random distribution can lead to non-uniform wear rates of the rotary tool. Nevertheless, rotary dressers with controlled diamond-distribution patterns (Fig. 24) provide a more robust dressing process [101,118]. In this respect, well-documented research has been done on: (i) the influence of diamond density, distribution and size on the efficiency of the dressing operation [144]; (ii) the subsequent grinding wheel performance [166]; and (iii) the subsequent workpiece quality.

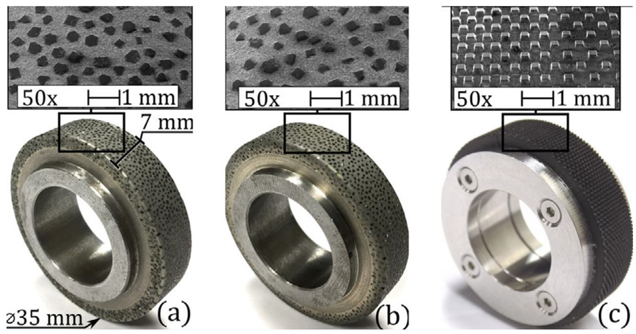


Fig. 24. Rotary dressers with (a) randomly distributed diamonds; (b) orderly distributed diamonds; and (c) controlled diamond shapes, dimensions and arrangements [224].

Recent advancements are further attributed to advances in bonding technologies. For example, Meister Abrasives introduced porous dressing tools based on a vitrified bond for self-sharpening ability. For applications requiring higher wear resistance, hybrid metallic-ceramic bonds were introduced. These tools still feature high porosity, but allow for better profile holding and stability. In the case where complex profiles need to be dressed, the hybrid dressing tools can be reinforced with CVD diamond rods, which are called cDD dressing tools (see Fig. 23(b)). Utilization of these tools gives lower dressing forces and results in a free-cutting grinding wheel with better form/size holding, thus enabling longer dressing intervals and, consequently, higher productivity.

Some recent advances regarding abrasive tools for grinding and fine finishing of automotive powertrain components include:

- Multi-segmented worms featuring a vitrified-bonded portion for roughing and a softer, resinoid-bonded, smaller-grit portion for grind-finishing of gears [74].
- Multi-grit wheels [223] featuring customized cBN grit shapes, properties [151] and grit concentrations [149] for crankshaft finishing.
- Macro-textured wheels with relief features (e.g. groves, holes) on the wheel surface to enhance cooling and ground surface quality [138].
- Micro-textured wheels with active surfaces containing micro-grits with controlled geometries, distributions and densities which make surface roughness [34], chip evacuation and cutting modes [32] easier to control.

The macro-textured wheels include grooves along the axis of the wheel while the wheel's active surface features different structures [214]. In some cases the structures are replaced by undercut relief grooves [106] and a tapered recess at the radial part of the leading edge of the grooves [245]. In addition, small-sized structures are proposed to reduce the dynamic instabilities induced by large-size grooves, which include scratched shallow grooves [5,169], micro blind holes [195], and geometrically-complex textures [183]. The aim of macro textures is to improve the coolant supply via special grooves on the wheel surface or by directly embedding a pressurized fluid chamber [71]. Such solutions require optimizing the geometries of

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the wheel inner-cooling channels [6]. In comparison with conventional wheels [137], the risk of burn is reduced significantly with external textures [138]. Improved delivery of the coolant into the grinding zone via inner channels can further reduce grinding temperatures [29]. It has also been reported that the macro textures have a positive effect on grinding forces, surface roughness and surface integrity [65,180]. Although much work has been done on textured grinding wheels, some interesting research questions still remain, such as which groove design maximizes the cooling effect. Some initial attempts have been made to reverse-engineer the groves based on thermal modelling [138]. Designing the grooves to run the process just under the burn threshold seems easy for simple operations like cylindrical grinding, but becomes difficult for wheels with complex peripheral shapes. Also, while it was reported that textured grinding wheels lower the temperature in the grinding zone, what happens to the fluid within these cavities (e.g. the fraction of fluid that fills the cavity and the distribution of the liquid vs. vapor phases) has yet to be studied.

More precise control of grinding outcomes necessitates micro-textures [33,267] to be produced on both conventional and superabrasive wheels. This typically involves laser ablation [36,187] to produce textures of V-shapes, cross-helix shapes and axially-eccentric shapes [246]. With regard to micro-texturing of superabrasive wheels, the first attempt made was to create different patterns on single-crystal diamond solids [33]. Afterwards, micro-textures have been successfully produced on polycrystalline diamond (PCD) [270] and polycrystalline cubic-boron-nitride (PcBN) solids [186]. Micro-textures can be also created on curved surfaces (e.g. around the periphery of the wheel) [35]. These unique tools, characterized by their uniform texture features (e.g. equal sizes, grit heights and kinematical distance), have not yet found applications in industry due to their complex and expensive manufacture. They will likely find niche applications in high-end operations that require low grinding forces [246]. Future advancements may include the design of micro textures (e.g. specifying requirements for shapes, densities, arrangements, etc.) through a better understanding of how they interact with the workpiece materials. This would allow for greater customization per application [32,67]. Moreover, future micro-textured grinding wheels could be considered as tools featuring geometrically defined cutting edges, which would require modification of the existing models for hybrid grinding tools that contain both defined and undefined cutting edges.

The capability of dressing also depends on the layout of the dressing system, i.e. the way in which the dressers are arranged in the grinding machine. Dressing solutions can vary, as in the case of the dressing systems in crankshaft grinders, shown in Fig. 25.

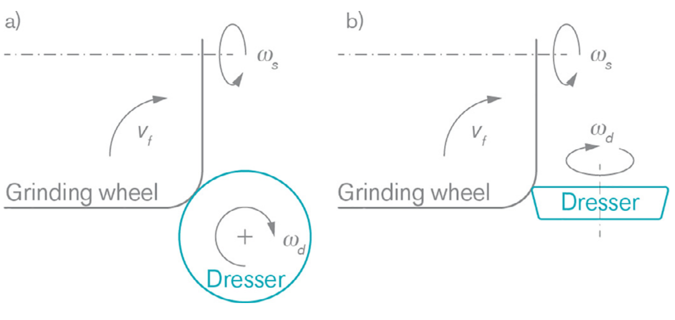

Fig. 25. Distinct dressing-system layouts in crankshaft grinders.

The grinding wheels have the same arrangement in the machine and rotate around the same axis, with a wheel rotational speed of ω_s. The dressers, however, have distinctively different arrangements, which give very different dressing results, even if the dressers rotate with the same dresser rotational speed ω_d and move with the same traverse velocity v_f. The Fives Landis dressing system (Fig. 25a) utilizes a uniform dresser roller − providing a robust dressing geometry which is insensitive to wear of the dresser. In contrast, the Junker dressing system (Fig. 25b) is more complex and features a cup-wheel dresser with one set of diamonds to dress the periphery (outer diameter) and fillet radius of the wheel, and another set of diamonds to dress the flank of the wheel. This solution is extremely sensitive to dresser wear, which affects the accuracy of the dressed wheel radius. This can lead to reduced quality of the ground crankshafts if not compensated for by a radius correction factor to minimize this error.

The above issues can be avoided by a better understanding of the dressing fundamentals, for which it is necessary to analytically model the different processes. Dressing can be quantified by the intensity, number, and depth of the diamond grit engagements [141]. The aggressiveness number in dressing [55] quantifies the intensity of the dressing interaction and captures the geometry and kinematics of the dressing contact. The number of times a grinding-wheel grit is hit by a diamond is determined by the collision number [28]. The quantitative assessment of different dressing processes, such as illustrated above, can be based on plotting the dressing specific-energy vs. the aggressiveness number [55] or analyzing the progression of the dressing aggressiveness for a given point on the wheel profile (e.g. radius) against the collision number. Finally, it has been shown that acoustic emission directly correlates with dressing power [7] and can be used to quantify the sharpness of the dress.

5.5. Advances in surface-texturing operations

Texturing operations vary in terms of the dressing strategy used to generate the patterned wheel and the degree of freedom to create specific geometrical features in the wheel [183]. Surface textures produced by grinding using conventional wheels with dressed macro textures [136] were first introduced by Stępień in 1989 [225]. His pioneering work involved texturing using surface or cylindrical grinding where the helical grooves were dressed into the wheel using a single-point diamond. More recent applications utilizing the same principle produce flat-textured surfaces [170,171,174] or use ultrasonic vibration-assisted grinding [105,261]. The generation of riblet-type structures by grinding was proposed by Denkena et al. [48]. Here, a SiC grinding wheel was dressed using a custom-made V-shaped diamond roller containing three different flank angles [47]. The dressing involved two consecutive plunges of the roller shifted in the axial position to generate the desired pattern in the wheel surface. To produce textured surfaces in bearings, the use of a kinematic modulation of grinding was proposed [234]. Different chevron-like microstructures were obtained based on the combination of differently modulated frequencies and amplitudes. Texturing can be achieved using a cBN wheel with a geometrically determined wheel topography that features controlled positioning of the grits and a uniform grit height imparted by diamond-roller dressing [119]. Based on the dressing technique that allows the inscription of a texture on the grinding wheel surface [183], recent advances offer a high-degree of flexibility in texture design (Fig. 26) − aided by a software to convert a 2D drawing of the desired texture into a control signal for the dressing unit [21].

Fig. 26. Examples of grinding-imprinted patterns [21].

Texturing by grinding necessitates an integer speed ratio between the wheel and the workpiece in order to obtain the correct pattern imprint and to avoid any overlapping of the texture. The industrial uptake of texturing requires on-machine capability for pattern-dressing of vitrified cBN wheels using rotary dressing tools, such as shown in Fig. 27. This system features an actuator and a flexible bearing housing to provide controlled micrometrical displacements of the diamond roller to dress the required micro-ramp geometry into the wheel. More details regarding the development, analysis and testing

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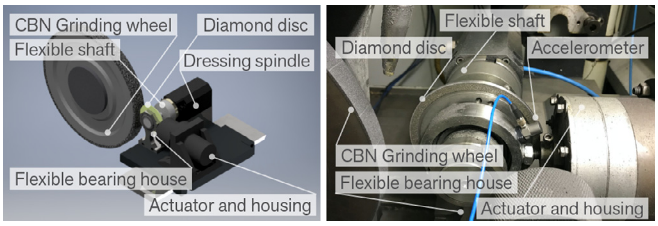

Fig. 27. Dressing units for patterning vitrified-bonded cBN wheels: (i) schematic representation; and (ii) assembled dressing unit and its major components [216].

of this system to produce micro-ramps are given in [216]. Further insights into the fundamental mechanics of grinding processes applied to the texturing of components are given in [52].

6. Fine finishing of automotive powertrain components

6.1. Fine finishing of gears

Fine finishing has a significant influence on the performance of gears in terms of efficiency, durability and NVH. Fine finishing of gears includes processes as diverse as WEDM [203], lapping of bevel or hypoid gears using an abrasive slurry [178,201,206], vibratory finishing [84,112,152], and magnetic-abrasive finishing [258]. Novel techniques, such as fluid-jet polishing [80,167], magnetic polishing [265] and magnetorheological finishing [247] might be feasible as well. Isotropic finishing (IF) of gears employs chemically-accelerated vibratory finishing [254]. More-widely used operations include gear honing [125,248], which can be used for fine finishing of internal and external gears (e.g. planetary and sun-gear rings). Gear honing uses an abrasive honing ring that has the geometry of an internal gear. It can achieve a surface roughness on the scale below R_z=1μm. Vitrified Al_2O_3 honing rings are typically used. However, softer resinoid bonds are able to achieve smoother surfaces but at the cost of productivity. Similar to conventional honing of bores [70,85], gear honing is characterized by a low cutting speed (0.5-10 m/s) when compared to gear grinding [125]. Moreover, it also mechanically induces high compressive residual stresses without the risk of burn while producing oblique honing marks on the gear flank that extend from the pitch diameter towards the tooth's addendum and dedendum, achieving improved lubrication and noise reduction. This technology is not well understood, but recent modelling of the geometry and kinematics enables the simulation of forces [13]. Moreover, modelling of the process-machine interactions enabled the estimation of (i) dynamic process forces and the displacements for a given workpiece waviness, and (ii) the resulting transmission error in the workpiece [133]. Further advancements of gear honing are discussed in Section 7 in view of machine application.

Grind-finishing of gears is implemented in a standard machine for continuous generating grinding. Grind-finishing is done in the same setup as grinding, but by using a special grinding worm that contains a softer, resinoid-bond finishing portion of the wheel which engages the workpiece directly after rough-grinding (which uses the vitrified portion of the wheel) (Fig. 28). This process is often erroneously

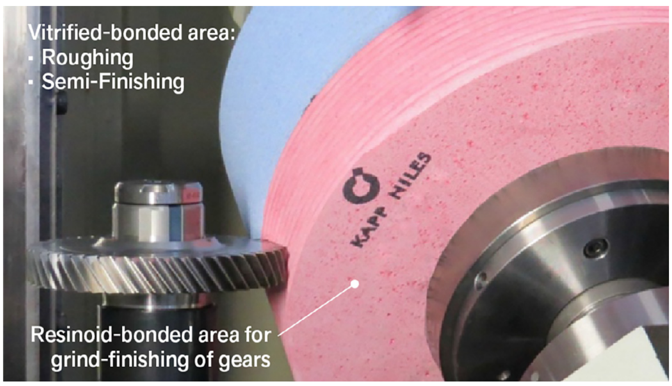

Fig. 28. Grind-finishing of gears (KAPP NILES GmbH & Co. KG).

referred to by wheel manufacturers, machine builders and end-users as superfinishing (or even polishing!) of gears. Such terminology should be avoided as it creates confusion with genuine superfinishing processes using a stone or tape, where the tool oscillates at high frequency to produce the characteristic cross-hatched surface [85]. Despite widespread use in industry, there is limited research available regarding grind-finishing of gears beyond commercial flyers.

The effects of a "softer" contact in fine finishing were demonstrated for discontinuous profile grinding of gears [87]. In this study, the parameters influencing the resulting gear noise included the surface roughness and geometry of the tooth flanks. By using elastic grinding wheels for fine finishing, a roughness of $R_z \leq 0.4$ µm (Fig. 29) could be achieved [87,111], along with additional surface-integrity benefits such as compressive residual stresses [243]. The bearing-area curves further revealed significantly higher material ratios for fine-finished surfaces. Due to the compliant bond, considerable elastic deformation of the grinding wheel causes shape deviation, which must be compensated for via process control [87]. The material-removal mechanisms for such a compliant grinding process [271] have only recently been addressed and modelled for general shape-adaptive grinding [260,272].

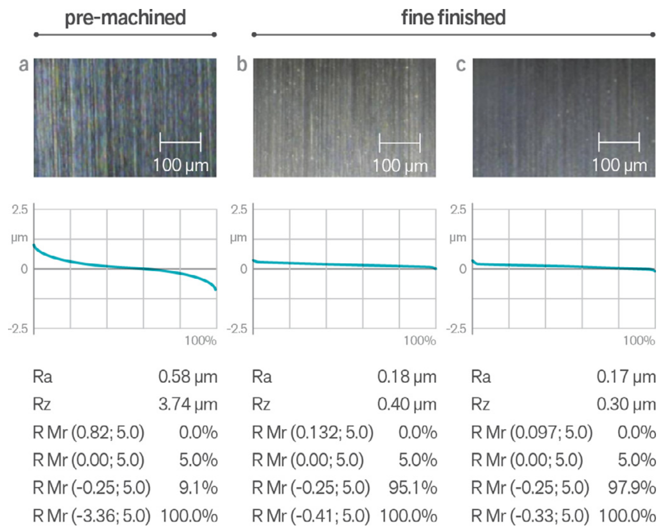

Fig. 29. Surfaces in fine-finished tooth flanks (discontinuous profile grinding) depending on wheel specification [87].

The frictional behavior in the mating gear pair relies heavily on the surface roughness of the finished gears. The theoretical perception is that better surface finishes reduce the asperity contact, which in turn minimizes the sliding friction coefficient and thereby enhances gear efficiency. The increase in efficiency was observed experimentally when comparing ground gears to isotropic finished (IF) gears [189], which revealed that IF gears are more robust than ground gears [2]. In an associated study, the effect of surface finish on the running-in of gears was analyzed. Here, the average surface roughness of the ground gears was four times higher than of the IF gears. The results implied that ground gears exhibited higher efficiency compared to IF gears at low (circumferential) running-in speeds (<2 m/s). However, IF gears performed better at speeds higher than 2 m/s irrespective of the applied running-in load. The explanation was that a rougher (e.g. ground) surface better retains lubricant at lower speeds. The running-in process to improve the conformity between two mating gears showed no influence on IF gears. For ground gears, however, a higher running-in load yielded higher mesh efficiency [2,218]. This indicates that the running-in process is necessary for ground gears, but can be eliminated in IF gears.

The durability of gears is also affected by breakage, surface-contact fatigue, plastic deformation, wear, etc. Recently, micropitting failure (a mode of surface-contact fatigue) has been increasingly observed by the gear industry. Every finishing process is different, producing unique characteristics in terms of roughness, residual stresses and material microstructure. A detailed study on how these characteristics evolve during cyclic loading and, in turn, their effect on micropitting was performed by Mallipeddi et al. [156], who analyzed ground, honed and IF gears, with honing and IF operations performed on pre-ground gears. In as-manufactured condition, the ground gears were rougher (R_a = 0.32 µm) than both honed (R_a = 0.18 µm) and IF (R_a = 0.08 µm) gears. The topography of ground-and-honed gears was comprised of adjacent peaks and valleys with irregular surface asperities, while IF gears exhibited a non-periodic (randomized) surface without any lay and asperities (see Fig. 30). In terms of residual stresses, honing induced higher compressive residual stresses followed by IF and ground gears. This observation was associated with the decrease in retained austenite after honing and IF. Efficiency testing further revealed that plastic deformation of surface asperities leads to the formation of micropits. The severity of deformation and micropitting was higher for ground-and-honed surfaces [182], but none of these defects were observed in IF gears [155,157]. Similarly, IF gears did not reveal any microstructural changes, such as plastic deformations, which can lead to surface cracking. Therefore, the surface finish seems to have a bigger influence on micropitting than residual stresses. This indicates that IF is necessary to prevent micropitting of gears [14,132,253,264]. An alternative to delay micropitting is to coat the gears [173].

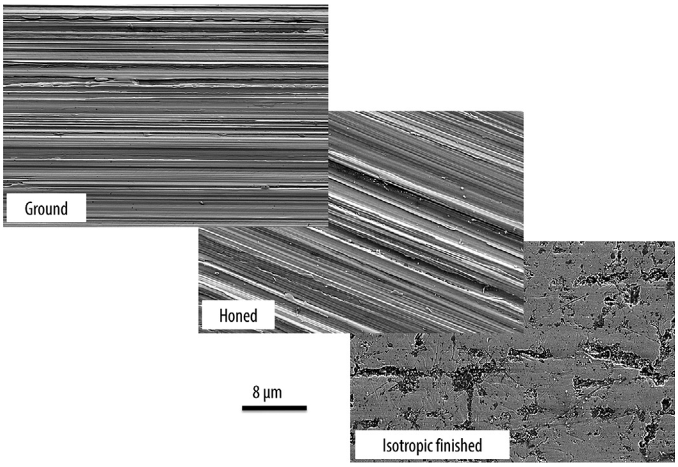

Fig. 30. Surface topography of ground, honed and IF gears [156].

6.2. Fine finishing of bearings and shafts

To a large extent, fine finishing of bearings and shafts refers to superfinishing. This process utilizes an abrasive stone or an abrasive tape (or a combination thereof). Here, the tool is radially pressed against the workpiece periphery and axially oscillated to produce a characteristic cross-hatched pattern. This technology was recently reviewed in terms of process parameters and quality aspects [85]. The most thorough experimental investigation of fundamental process mechanics still dates back to the 1990s [194,238]. Recent benefits also included substitution of straight mineral oils with novel water-based fluids that demonstrated equivalent process performance [59]. The capability of tape finishing was recently compared to vibratory finishing and ball burnishing [41]. These fine-finished surfaces were superimposed on turned workpieces and analyzed in terms of surface integrity. Compared to vibratory finishing, tape finishing produced lower compressive residual stresses only on the surface, which is not a surprise in view of the limited mechanical impact. Deep valleys on the surface, however, provided an improved oil-retention capability. A similar study investigated the effect of stone finishing after hard turning on achievable surface roughness [76].

From an end-use(r) perspective, the aim of superfinishing is to produce a surface that is wear-resistant, reduces friction and has excellent emergency-running properties. An example of such a surface has a minimum of peaks protruding from the surface (e.g R_{pk} < 0.03 µm), a distinct core roughness range (e.g R_k < 0.13 µm) and sufficient valley depth (e.g. R_{vk} > 0.08 µm) for oil retention. From a production perspective, these demands are somewhat contradictory. For example, a finishing tape with fine grits is suitable for producing a plateau surface, but it cannot achieve sufficient stock removal to completely remove the base surface topography created by grinding nor generate a surface roughness to improve emergency-running properties. A typical superfinishing process implemented in the industrial production of crankshafts includes a two-stage tape-finishing processes: it first removes the grinding-induced topography (R_z = 3-4 μm), and then in the second step forms a plateau surface [193]. This finishing strategy is constrained by the capability of the tape and is sensitive to the base surface texture that exists from pre-grinding. A more advanced approach is to now consider a three-stage tape-finishing operation (Fig. 31), such as follows:

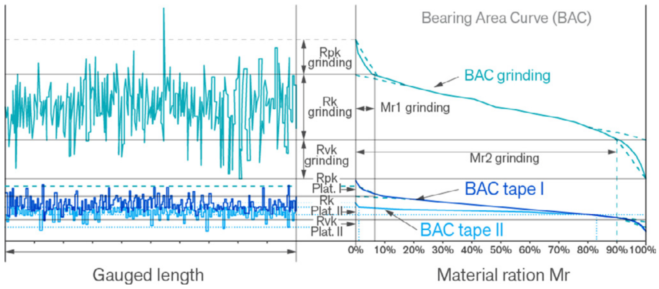

Fig. 31. Three-step superfinishing of crankshafts (Supfina Grieshaber GmbH & Co KG).

- Step 1: Base roughness. A rough abrasive tape is used to remove the grinding marks and produce a base surface roughness. At the same time, friction is improved, e.g. via reduction of waviness from pre-grinding.
- Step 2: Leveraging on R_k and R_{pk}. A plateau-shaped surface is formed with a finer grit.
- Step 3: Final leveraging on R_{pk}. The last remaining roughness peaks on the surface are cut off and the load-bearing capacity is increased.

Process optimization here involves proper selection of the abrasive tape (grit size) and hardness of the shoes for each step.

7. Machines for grinding and fine finishing of automotive powertrain components

The 2017 CIRP keynote paper by Wegener et al. [250] critically reviewed the potential effects of major industrial trends such as resource efficiency, customization, digitalization and connectivity in grinding machines. The effects of transitional changes in the automotive industry, however, were not specifically discussed. The uncertainty about the future market uptake of the different automotive powertrains constitutes a significant reason for reduced orders and production volumes of machine tools since 2017. This resulted in a sharp decline in machine-tool market growth in 2019. Nevertheless, the automotive industry still leads the market with respect to machine-tool consumption. Moreover, machine manufacturers continue to emphasize large-scale production lines for conventional powertrain components that have been in use for decades, despite the current situation. This situation will not drastically change in the near future due to still relatively low shares of EVs. Our survey hints that the traditional machine-tool portfolios will be adapted and expanded to cover some of the observed future needs. Since machine tools are modular, it will not be too difficult to adjust the machine design to new customers' needs as is always the case in an industry where the complexity of machine tools is directly related to customers' requirements. In these circumstances, the focus will continue to be on increased flexibility and on the capability to produce functional surfaces. Until the advent of EV, the size and shape ranges of ICE components have been rather similar. However, future components necessitate a shift towards higher, automation-enabled flexibility and easy customization, in addition to the trend toward smaller and faster machine tools. Machine builders are taking the changing automotive market seriously and are pushing fast forward this transformation. In the long term, it seems absolutely necessary to embrace the market for EVs in the whole manufacturing value chain – from component manufacturers to machine builders and automation suppliers.

7.1. Grinding machines

Advances in grinding machines for automotive powertrain production still mainly refer to dedicated camshaft and crankshaft grinding machines. The first CNC cam grinder in 1969 already featured profile-error compensation due to wheel wear, along with CNC dressing of the wheel [100]. The CIRP community was involved in this technology development from the early years of cam grinders. McKeown and Dinsdale discussed the design of a high-precision CNC cam grinder in 1974 [160]. This design, along with the variable workhead speed (C-axis) and proprietary control system [192], resulted in the production series of so-called “orbital” grinders in 1983 by (then) Landis Lund. A decade later, in 1994, the same company developed and introduced the twin-wheelhead CNC cam grinder featuring two grinding spindles for increased capacity and higher production rates. These cam grinders can implement a temperature-controlled grinding process [128] (see Section 5.3) where the two individually-controlled wheelheads are CNC-synchronized with the workhead rotation. The efficiency of workhead-wheelhead synchronization depends not only on the control system, but also on machine limitations for achievable speed, acceleration and jerk. Machine limitations further determine the motion performance of the wheelhead. Here the limitations on how fast the wheelhead can accelerate back and forth and how quickly it can change direction depend largely on the machine drive system. For example, the limitations of a linear motor and ballscrew drive were compared for two different camshaft grinders. The linear motor was better-performing compared to the ballscrew drive, achieving 70% higher speed, 80% faster acceleration and 50% larger jerk [128,250], which can result in a 20% shorter cycle time for constant-temperature grinding process. A key element to accomplish this is the hydrostatic-bearing linear motor slide.

Constrained hydrostatic bearing slides are well known and have been used on many machines. They require tight tolerances on the long guideways and bearing surfaces. When investigating the use of permanent-magnet linear motors, several innovations emerged. As seen in Fig. 32, the linear motor is placed between the hydrostatic rails. With slide loads known and hydrostatic pads designed to balance them, the system operates on a 25-30 μm oil film [190]. An additional benefit of the constant linear motor attraction force is its use for braking. A requirement for linear motor axes is the ability to brake the system during faults or power loss. By turning off the vertical hydrostatic bearing pads, the motor attraction force causes the cast iron slide surfaces to function as a brake. The position and velocity controllability are functions of the servo amplifier and feedback. High-performance industrial servo controls typically have a 62.5 μs current loop rate, a 125 μs velocity loop rate and a 250 μs position loop rate. Velocity loops operate at over 200 Hz. and position loops over 20 Hz. Optical linear encoders provide better than 10 nm resolution. These slides operate at sub-micron positioning errors while contouring crankpins at up to 60 RPM. The advantages of this system are increased performance, decreased cost and increased reliability. Today there are thousands of these slides operating in camshaft and crankshaft grinding machines around the world.

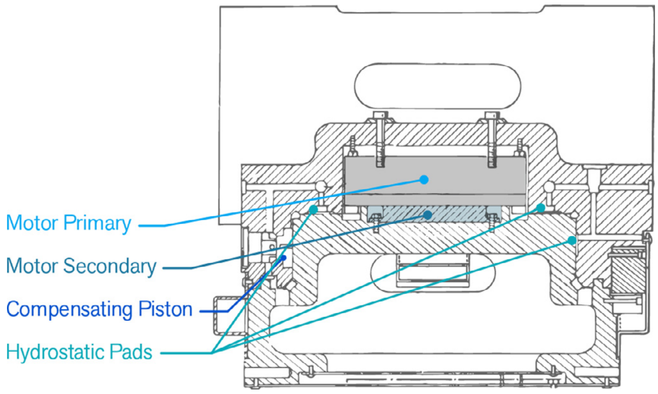

Fig. 32. Hydrostatic linear motor slide (Fives Landis Corp).

7.2. Fine-finishing machines

This section does not provide an extensive review of the state-of-the-art of fine-finishing machines. Recent developments are illustrated by two commonly used operations in industry: gear honing and superfinishing of bearings.

Recent developments in gear honing aim at increasing the cutting speed to maximize the process productivity. Until the 1990s, cutting speeds rarely exceeded 5 m/s. The new generation of honing machines is much stiffer, with enhanced spindle and workhead kinematics, enabling honing with cutting speeds of 15 m/s. The cutting speed depends on the rotational frequency of the workhead and the cross-axis angle between the workpiece and the honing ring. While the cross-axis angle is limited with respect to the machine geometry and gear-interfering contours, it is easier to optimize machine kinematics. A typical gear-honing machine uses a tool spindle with bearings larger than the honing ring. The machine drives the honing ring while the workpiece (gear) is simply brought to the meshing with the honing ring. The honing ring sits directly beneath the bearings to achieve a high stiffness and to allow the workpiece to be clamped with a tailstock. This type of tool spindle is called a ring-type honing head (Fig. 33).

The bearings are the main limitation, constraining the achievable rotational frequency to 3,000 RPM. Further spindle development includes a cup-type honing head (featuring smaller bearings), which is suitable for applications without the demand for a tailstock. The goal was to reach 5,000 RPM for the tool, to increase the maximal cutting speed up to about 25 m/s. Achieving the required machine stiffness is challenging due to the positioning of the bearings and the higher operating speeds. The higher temperatures of the spindle housing affected bearing preload (stiffness) and machine accuracy, which were tackled via integration of an advanced cooling system and passive damping of vibrations. These solutions have now been commercially implemented in the latest-generation machines, enabling gear honing with reduced cycle times and improved quality of the finished gear profiles. In addition, high-performance gear honing has been developed. It features a separate drive for the workpiece which is synchronized with the drive for the honing ring. This enhances the material removal (reduced cycle time) and enhances the quality by reducing the pitch error [133]. Other developments include capability of honing two gears with different diameters on the (synchronized) stepped pinion in a single setup. Here, the B-axis compensates the center offset between the two honing rings.

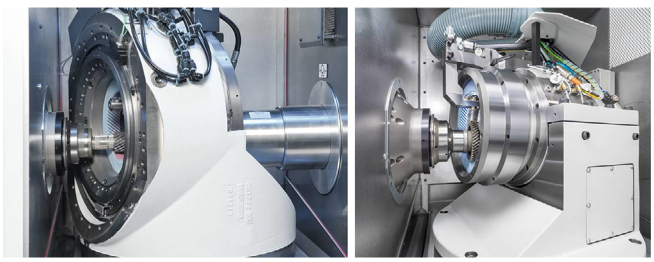

Fig. 33. Ring-type (left) vs. cup-type (right) honing head (Gleason-Pfauter Maschinenfabrik GmbH).

The solution for flexible grinding of bearings using an OD/ID grinding machine with twin turrets was described above in Section 5.1. Similarly, flexible machine solutions are also needed for fine-finishing operations to support the requirements for fast changeovers to new components or for fine finishing of smaller batches. These drivers led Supfina to recently develop a modular, highly flexible finishing cell. The cell, shown in Fig. 34, features a 6-axis robot used not only for loading and unloading components to the workspace, but also for implementing finishing processes such as the tape-finishing of the shoulders of roller bearing rings. The force-controlled robot also provides the rotational frequency to the workpiece and applies the necessary force to the finishing tape, whereas the superfinishing unit carries out the required oscillation movement of the finishing tape. As soon as the process is done, the robot places the component on the conveyor belt and picks up a new blank to be machined.

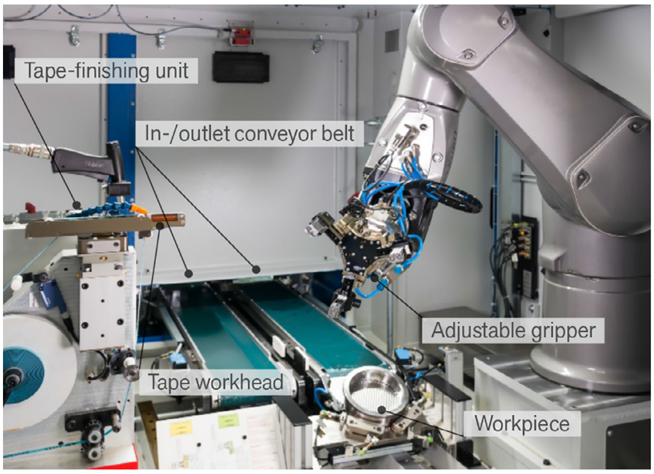

Fig. 34. Supfina's R-Cell enabling a flexible robotized finishing (Supfina Grieshaber GmbH & Co KG)

The case study illustrated here is only one variant of flexible fine finishing, which can easily be extended to different applications. For this, the requirements need to be carefully analyzed − not only for the fine-finishing process, but also for entire production chain. As shown here, the automation can take over a large part of the finishing and provides a new dimension of flexibility for a wide range of components. It is important to add that the presented cell not only covers typical fine-finishing processes, but can also integrate processes such as belt grinding, deburring, measuring, marking and cleaning of the components.

8. Summary and outlook

The automotive industry is facing major challenges driving its transformation: autonomous driving, electrification, connected vehicles and new ownership models. Electrification has the most profound impact on the industry and its customers. Currently, the entire world is working on new solutions for future mobility. The need to drastically reduce emissions within a decade is clearly evident, but electrification is not the ultimate solution to all environmental challenges as its positive impacts are not always properly assessed in a lifecycle context. Moreover, the availability of renewable-/biofuels and hydrogen will offer a new lever of sustaining non-electric vehicles. This means that automotive powertrain components such as gears and shafts will not simply disappear or drastically reduce in volume. Rather, as the powertrain portfolio diversifies (from ICE to HEV/PHEV, EV, FCEV), the powertrain components will become more complex, with even more changes.

The new requirements are pushing the transformation of longstanding principles in the automotive industry and are advancing numerous manufacturing processes, including grinding and fine-finishing technologies. In future automotive-powertrain production chains, the current material-conversion processes from raw materials to finishing could be radically changed by emerging technologies, whereas the current grinding sequences are replaced with more-flexible, multi-surface-finishing and fine-finishing capabilities. The discrete processes may be integrated into highly-flexible systems which can reduce the tooling cost and the changeover time. The future scenarios are outlined in this paper, but their further refinement as well as real implementation data (KPIs) are needed to enhance their accuracy.

Gears have the toughest requirements for surface finish and geometrical accuracies (e.g. new lead modifications and asymmetric gears). Major advances were achieved and implemented on machines with respect to modifying the geometry and kinematics of the gear-grinding and honing processes. Both processes have their advantages and disadvantages, and, therefore, one cannot say that gear grinding is better than gear honing. Each technology has its own specific capability determining its use. For example, fine finishing of internal gears is rarely done by honing, because the process is not sufficiently robust. More research is still needed to further develop this technology.

The advances in texturing highlighted in this work are not yet readily available for gears (e.g. for texturing the tooth flanks), whereas the last generation of camshafts and crankshafts incorporate features such as the convex geometry of the bearing surfaces that can be textured. Texturing by grinding has emerged as a viable and economic alternative for producing surface micro-features on automotive shafts and bearings to improve lubrication and hydrodynamic sliding. In the past decades, significant advances that demonstrate the capabilities of texturing have been made in different laboratories around the world. The biggest challenge remaining is how to implement this operation in real-world production. Retrofitting the dressing systems in existing grinding machines is feasible, as well as incorporating the solutions into the design of new grinding machines. Additional challenges are related to the dressing and pattering of grinding wheels as well as the further development of process monitoring to control the robustness of texturing in an industrial environment.

This work has also indicated that machines do not always come supplied with optimal processes. This necessitates the joining of forces of machine builders, end-users/OEMs and researchers to work proactively on a number of research areas such as (i) the modelling of geometry, kinematics and temperatures in complex grinding processes (e.g. gear, camshaft/crankshaft, double-disc, tapered rollers); and (ii) the advancement of abrasive products (bonds, macro and micro-textures, etc.).

Finally, this keynote is CIRP's first systematic attempt at addressing the challenges of transforming automotive industry; in this case through the (narrow) lens of finishing technology. The received contributions by industrial partners have been overwhelming and serve as an opportunity to further bridge the gap between academic research and industrial development. The industry should continue with an open dialogue, whereas researchers should pursue advancing technologies for the production of future powertrains at an accelerated pace. Moreover, this transformation is creating an enormous demand for competence development for working professionals. The electrification will affect a great number of engineers in the industry who need new skills to sustain the competitiveness of their companies. In this respect, it is also necessary to integrate the latest research findings into education and training programs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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